UNIVERSIDADE FEDERAL DO PARANÁ

ARTUR SASS BRAGA

LEAKAGE AND ENERGY IN WATER SUPPLY SYSTEMS: AN EXPERIMENTAL APPROACH

CURITIBA

2016

ARTUR SASS BRAGA

LEAKAGE AND ENERGY IN WATER SUPPLY SYSTEMS: AN EXPERIMENTAL APPROACH

Thesis presented as partial requirement for Master degree in the Graduate Program of Water Resources and Environmental Engineering, Universidade Federal do Paraná
Supervisor: Cristovão Vicente Scapulatempo Fernandes
Co-supervisor: Sérgio Michelotto Braga

CURITIBA

2016

B813l

Braga, Artur Sass
Leakage and energy in water supply systems : an experimental approach/ Artur Sass Braga. – Curitiba, 2016.
148 f. : il. color. ; 30 cm.

Tese - Universidade Federal do Paraná, Setor de Tecnologia, Programa de Pós-graduação em Engenharia de Recursos Hídricos e Ambiental, 2016.

Orientador: Cristovão Vicente Scapulatempo Fernandes – Co-orientador: Sérgio Michelotto Braga.
Bibliografia: p. 113-116.

1. Água - Distribuição. 2. Água - Distribuição - Vazamento. 3. Eficiência. I. Universidade Federal do Paraná. II.Fernandes, Cristovão Vicente Scapulatempo. III. Braga, Sérgio Michelotto . IV. Título.

CDD: 628.144

TERMO DE APROVAÇÃO

ARTUR SASS BRAGA

"Leakage and Efficiency in Water Distribution Systems: Na Experimental Approach"

Dissertação aprovada como requisito parcial à obtenção do grau de Mestre, pelo Programa de Pós-Graduação em Engenharia de Recursos Hídricos e Ambiental do Setor de Tecnologia da Universidade Federal do Paraná, pela comissão formada pelos professores:

PRESIDENTE:

Cristovão Vicente S. Fernandes
Universidade Federal do Paraná
Orientador

MEMBROS:

Sérgio Michelotto Braga
Universidade Federal do Paraná
Co-orientador

Fábio Veríssimo Gonçalves
Universidade Federal do Mato Grosso do Sul

Tobias Bleninger
Universidade Federal do Paraná

Daniel Costa dos Santos
Universidade Federal do Paraná

Curitiba, 24 de fevereiro de 2016

To Elis, my reason and inspiration

ACKNOWLEDGEMENTS

This research work is a result of a great number of ideas, which has been born and developed in many different minds. Therefore, I am really grateful for all those people who shared any idea with me and, consequently, have contributed scientifically with this master thesis. Among those people I want to highlight my friends Julio W. Y. Bernardo, Michael Mannich and João Pedro B. Nadas and the professor Daniel C. Santos, which were aways available to help me.

I also appreciate the water utility *Companhia de Saneamento do Paraná – SANEPAR*, not only as the master's funding company but, and most important, as contributor of ideas, representing the real engineering problems of water distribution systems in Brazil. Several meetings with the SANEPAR engineers Gustavo Possetti and Marcelo Depexe have guided the research development of this research and improved the final results. I am grateful for their engagement in this study and their effort to build a better water distribution system in Paraná.

The experimental work developed in this thesis it was only possible by the support of workers team from the Center in Hydraulic and Hydrology of Paraná, represented by Ronaldo Zacarias Silva and Idulino Bráz Bonamigo, to whom I give my heartfelt thanks.

I dedicate a special thanks to my supervisor Cristovão V.S. Fernandes, who has spent uncountable hours thinking, reflecting and discussing with me about my research and my academic life. During these years as his master student, Cristovão overcome all his responsibilities as supervisor, and he became a great friend who I respect and admire a lot.

I also dedicate special thanks to my co-supervisor Sérgio M. Braga, my uncle and godfather, who guided me since my first undergraduate year to ingress in the “research world”. My opportunities and research motivation were many times potencialized due to his guidance and all support in the university.

Lastly, beyond the academic life (or “work”), many others are essential and have supported me, specially through challenging period of doing a master's degree. In such a context, anyone have supported and motivated me more than my wife Elisangela S. P. Braga, to whom I am really grateful to her choice of sharing her's life with me. I also dedicate special thanks to my friends João Pedro B. Nadas, Ciro C. Rodriguez, Murilo B. Lense and Mateus Manfrinato; to my parents Mauro M. Braga, Cleis W. S. Braga; to my brother André S. Braga and to my family. Without this people neither my research nor my life would have have any sense and meaning.

“Science is the manifestation of a fraction of human potential.”

Wayne Chirisa

ABSTRACT

Leakage in drinkable water distribution systems have been causing significant water and energy losses, especially in developing countries. The leakage impacts over the systems performance are mainly addressed to the increase of pumped flows required to supply the usual demand and additional leakage flows. The extra flow implies in greater input energy, higher friction losses and a general unbalance of the system operational conditions, which cause inefficiency. In such a context, to address the increase of leakage in water networks it is necessary to understand its causes, characteristics and consequences.

In this research an intensive experimental investigation was performed regarding leakage through round hole orifices in a laboratory pipe system. The focus of the experimental approach was developing relationships between the leakage characteristics, the system hydraulics and the system's energy balance. Such a holistic experiment is rare in literature, specially because the leakage water losses traditionally draw the researchers attention to hydraulics, leaving aside impacts in efficiency and energy losses.

Unexpectedly, the results show that the understanding about leakage hydraulics in water distribution systems still needs improvement, in order to better quantify leakage flows and develop reliable hydraulic models. The experiments with round orifice leaks pointed out that the required advances are mainly addressed to the leakage flow regime, which is usually adopted as a complete developed turbulent flow. Since this assumption was not necessarily verified in the experimental data analysis, better efforts are needed to understand the impacts of different leakage Reynolds numbers in leakage flows.

Results regarding the leakage impacts in the system energy balance have shown that the increase of leakage have caused a greater inefficiency, which means that large amounts of energy were required to supply similar demand conditions in the presence of larger leakage flows. However, the analysis of individual components of systems energy losses (e.g. continuum head losses, local leakage head loss, hydraulic pump energy losses) points to different sensibility levels according to leakage conditions, which sometimes could even show better performance for higher leakage. It is important to note that the relationships developed in this research are binded to the laboratory system employed, but could guide further research in other systems.

Key-words: Leakage, Energy Efficiency, Water Distribution Systems

RESUMO

Vazamentos em redes de distribuição de água potável vêm causando perdas significativas de água e energia, especialmente nos países em desenvolvimento. Os impactos dos vazamentos sobre a performance dos sistemas são principalmente causados pelo aumento do bombeamento de água, necessário para suprir a demanda usual adicionada de fluxos de vazamentos. A vazão extra implica em maiores quantidades de energia, aumento das perdas contínuas pelo atrito e condições de operação desbalanceadas, que causam ineficiência no sistema. Nesse contexto, para conter o aumento de vazamentos nas redes de distribuição é necessário entender suas causas, características e consequências.

Na presente pesquisa é desenvolvida uma intensa investigação experimental acerca de vazamentos por orifícios em um sistema de distribuição em laboratório. O foco da abordagem experimental foi desenvolver relações entre as características dos vazamentos, a hidráulica do sistema e o balanço energético do sistema. Experimentos incorporando tantos aspectos das redes de distribuição são raros na literatura, pois tradicionalmente o interesse de pesquisadores sobre a hidráulica dos vazamentos ofuscou os impactos sobre a eficiência energética do sistema.

De forma inesperada, os resultados demonstraram que o conhecimento da hidráulica de vazamentos em redes de distribuição de água ainda requer mais estudos, de modo a quantificar de forma confiável as vazões de vazamento em modelos hidráulicos dos sistemas. Os experimentos com orifícios apontam que o principal avanço necessário consiste da incorporação dos regimes de escoamento nas equações que descrevem o comportamento hidráulico dos vazamentos.

Os resultados acerca de impactos de vazamentos no balanço de energia demonstraram que o aumento de vazamento causou maior ineficiência, o que significa que maiores quantidades de energia foram necessárias para atender condições similares de demanda na presença de vazamentos. Entretanto, a análise de componentes individuais das perdas de energia (e.g. perdas por atrito, perdas nas bombas hidráulicas) apontou para diferentes taxas de variação de acordo com as vazões de vazamento. Algumas componentes individuais do sistema inclusive apresentaram maior eficiência para condições de vazamento. Destaca-se que as relações desenvolvidas neste trabalho estão vinculadas ao sistema de laboratório empregado, porém, tais resultados têm grande potencial para guiar novos estudos em outros sistemas.

Palavras-chaves: Vazamentos, Eficiência Energética, Sistemas de Distribuição de Água

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

WSS	Water Supply Systems
WDS	Water Distribution Systems
NRW	Non-Revenue Water
PLC	Programmable Logic Controller
LENHS	Laboratory of Energy and Hydraulic Efficiency in Sanitation

LIST OF SYMBOLS

ρ	Constant water density = 1000 kg/m^3
g (m/s^2)	Gravitational acceleration
M (kg)	Mass
L (m)	Length
t (s)	Period of time
z (m)	Elevation
π	Constant = 3.14159265359 ...
Q (m^3/s)	Flow
A (m^2)	Area
H (m)	Energy head
h (m)	Pressure head
Δh (m)	Pressure head variation
h_f (m)	Pressure head loss due to friction
D (m)	Diameter
W (m)	Wall Thickness
V (m/s)	Average velocity magnitude
$\vec{u}$ (m/s)	Instantaneous velocity vector
E (W)	Energy flux, Power
ΔE (W)	Energy flux variation
∇	Differential operator
ϵ	Contraction coefficient
ϕ	Velocity coefficient
ξ_0	Coefficient of fluid resistance
C_d	Discharge coefficient

$N1$	Exponent coefficient
C_L	Leakage coefficient
$\mu\ (N\,s/m^2)$	Fluid dynamic viscosity
Re	Reynolds number
m	Coefficient of area expansion for the FAVAD equation
$K\ (m/s)$	Coefficient of soil permeability
C^*	Geometry parameter
N	Number of pipe sections
f	Darcy-Weisbach friction factor
ψ	Amplitude of dispersion
σ	Standard deviation
χ, ζ	New leakage coefficients
η (%)	Hydraulic pump efficiency
$\xi_{x,y}$	Ratio of variable x according to variable y
$Pump$ (%)	Hydraulic pumping system capacity adopted with frequency inverters
$\omega\ (Hz)$	Hydraulic pumping system rotational speed
	Subscripts:
up	Cross section upstream leakage
$down$	Cross section downstream leakage
$leak$	Cross section of the leakage
VC	Cross section of the Vena Contracta
$orifice$	Related to the orifice
$pipe$	Related to the pipe stretch
ext	Related to pipe stretch external conditions
f	Related to friction
i	Pipe index

diss	Dissipation of energy
elec	Electric energy

CONTENTS

1 INTRODUCTION

“A story has no beginning or end: arbitrarily one chooses that moment of experience from which to look back or from which to look ahead.”

Graham Greene, The End of the Affair

To secure water supply for urban areas represents one of the century goals of the millennium society, being the *modern water supply systems* the principal infrastructure involved. These systems are basically composed by water storage, treatment and distribution, commonly called *water distribution systems* (WDS).

WDS are the main engineering solution to transport large amount of drinkable water throughout cities, which are usually composed by hydraulic pumps, reservoirs and kilometers of a network pipes. These systems have been constructed with an infinity of individual parts, to attend different supply characteristics over distinct topologies, which makes each system singular with a unique hydraulic behavior.

In most countries, the access to *drinkable water* its considered a *right of everyone*, but in order to supply population demands, environmental impact studies and several infrastructural and operational costs must be met (MAYS, 2000). Thus, is also a *duty of everyone*.

In the case of WDS, although initial planning and infrastructure installation usually represents a large investment, the operational costs of the system will become a burden for both society and the environment. Therefore, efforts to improve WDS performance and to minimize operational costs can save significant amount of *water* and *energy*, fundamental resources for life and development. The present research is based on the concept of a search for optimum use and better performance of *water* and *energy* in WDS. Briefly, the performance of a WDS consists of systems capacity in supply drinking water demands with minimal costs, where the electrical power consumption are usually the larger operational costs involved. Therefore, a rule of thumb to improve WDS performance is to minimize their water and energy requirements, where the first is mainly impacted by *excessive demands for water* and *water losses*, and the second is hampered by the sum of *individual parts low efficiency*.

Illustrating the demand of energy by WDS, Brailey and Jacobs 1980 (apud COLOMBO; KARNEY, 2005) have estimated that 7% of United States electric power was addressed to supply municipal water utilities, being almost 90% of it regarding operational costs. Moreover, Cabrera et al. (2015) points that estimations of electrical energy consumption in WDS at Europe for 2012 reached up to $109\,TWh = 392.4PJ$, equivalent of a year power average of $12.4\,GW$ (Itaipu hydroelectric power-plant installed capacity is 14 GW). Unfortunately, information about WDS energy use efficiency are scarce and related to individual systems characteristics, thus to estimate how much energy could be save from the total consumption is challenging.

The energy efficiency in WDS depends on several factors, such as: hydraulic pumps performance, pipe friction, excess of supplied energy, system design and water losses (COLOMBO; KARNEY, 2002; CABRERA et al., 2010; CABRERA et al., 2015; SCANLAN; FILION, 2015); these factors have to be considered by those in charge of developing actions for improving the systems performance. In particular, the case of impacts caused by water losses in WDS are also associated to *waste of water* concerns, which are linked to environmental impacts and water treatment costs, or even intangible impacts related to water scarcity. Furthermore, water losses are pointed as one of the major sources of WDS inefficiency (COLOMBO; KARNEY, 2002). Farley *et al.* 2008 (apud XU et al., 2014a) estimates that 35 % of total world input volumes of water in WDS are lost, which impacts regards both energy and water wasting.

It is challenging to estimates the total costs related to water losses in WDS, because the increase of system pumped flows could affect all system behavior, and impact its whole performance. Hydraulic pumps spend more energy to pump more water, continuum head losses over the system increase due to higher flow velocities and systems design characteristics could be less efficient with changes in system flows. Hence, in order to minimize the impacts of water losses to improving system performance it is required a better comprehensive approach of WDS, aiming to find the better strategies to cope with this complex problem.

In short terms, water losses in WDS are strongly tied to energy efficiency. The comprehension about their impacts over system costs have potential to improve systems performance. In such a context, this research presents a detailed analysis of a laboratory scale WDS, where water losses were simulated in controlled conditions. Therefore, the water losses were evaluated regarding their hydraulic aspects and impacts over the system electrical energy usage. The results shown that water losses could significantly change system operational conditions, and have negative impacts upon its average performance.

1.1 THESIS RELEVANCE

In a World scenario characterized by an *energy crisis* (U.S. Department of Energy 2006 apud CASSA; ZYL; LAUBSCHER, 2010) and crescent concerns about *water scarcity* (XU et al., 2014a), the WDS performance play a key role for ensure a reliable and sustainable supply of drinkable water. This research focus on WDS performance, including water losses assessment by leakage and their associated energy losses (COLOMBO; KARNEY, 2002).

In order to improve the knowledge about leakage and the energy use in WDS operation, an experimental setup was proposed to simulate leaks in laboratory scale. Since related experiments focused on energy losses were not found in literature, the investigation was performed simulating leaks from round orifices drilled in pipes wall, to reduce the leakage phenomenon complexity.

Research results presents a detailed analysis on round orifices leakage hydraulics, which have shown to improve previous literature reports. Initially, the leakage through round orifices hydraulics appeared to be well understood, based on several laboratory experiments related (WALSKI et al., 2009; CASSA; ZYL; LAUBSCHER, 2010; FERRANTE et al., 2014; ZYL, 2014). However, significant differences from literature results were found, which can be consequence of the distinct experimental approach (the experiments were conducted in a laboratory WDS, with higher network complexity from most previous studies about leakage). Hydraulic behavior of tested leaks regarding pipe material and diameters for different system conditions is analyzed.

Additionally, the energy losses related to leakage were prospected by the evaluation of individual sources of inefficiency associated, such as continuum and local head losses and influence in hydraulic pumps performance. The experiments results ported out the existence of similar energy losses in real WDS. Therefore, they could be used to establish new methods to account for leakage energy losses in real systems, aiming improve their performance.

1.2 OBJECTIVES & METHODS

The main goal of this research is to investigate the leakage hydraulics in WDS and its impacts over the systems energy use, throughout the development of a laboratory experiment. The experimental approach have been focused on leakage phenomenon mechanics and system energy transformations, mostly seeking to establish relationships between WSS variables (flows, pressures, pipe diameters), leakage characteristics (leakage flow, leakage velocity, orifice diameters) and energy efficiency variables (consumed electrical energy, continuum head losses, local head losses, leakage hydraulic energy, delivered hydraulic energy), for a laboratory scale WDS.

There are two *specific goals* in this work: to evaluate the leakage hydraulic behavior and to estimate the leakage impacts in system energy use. This goals match to actual problems in WSS and have been addressed to improve leakage control actions by water facilities.

In order to evaluate the leakage hydraulics, direct measures of leakage flows and system pressures under many conditions were performed in the laboratory network. Four orifice diameters were individually drilled in four distinct pipes (combination of two materials and two diameters) and tested in the laboratory system for pressures head range of $5 - 50\,m$. Therefore, the experimental data were analyzed according to two main relationships reported in the literature: the *orifice equation* and the *power equation*; aiming to assess their limitations and coefficients behavior in function of leakage characteristics.

In the case of the system energy use, three possible sources of system energy inefficiency were analyzed in order to estimate leakage contribution in energy losses: hydraulic pumps performance, continuum head losses and local head losses. The leakage influence upon these sources were estimated mainly throughout the *energy equation*. It was assumed a complete thermal equilibrium of the system and steady flow conditions, to allow a energy balance between the electrical energy input and the hydraulic energy delivered after the leak. Furthermore, the proportional energy losses associated to leakage were also compared with the leakage flow ratio for the system, aiming to built dimensionless indicators to assess these impacts.

1.3 ORGANIZATION

This document is organized in seven chapters, detailed below:

1. *Introduction*: Context of Leakage problem in WDS.

2. *Leakage in Water Distribution Systems*: Literature review about leakage in WDS and a detailed description of the problem, focusing hydraulic concerns.

3. *Experimental Approaches in Leakage Simulation*: The use of laboratory experiments to investigates leakage hydraulic behavior and the proposition of the experiments developed in this thesis, which aimed to study leakage relationships regarding the system energy use also.

4. *Leakage Analysis from a Hydraulic Perspective*: Results regarding tested leakage hydraulic behavior, assessment of reported relationships to estimates *leakage flow through round orifices.*

5. *Leakage Impacts in WDS Performance*: Results regarding the leakage influence in system energy use. Estimation of the energy losses associated to leakage, and its overall impacts in the laboratory system performance.

6. *Final Remarks*: Thesis main conclusions about experimental results, and a reflection about further research necessary to expand the understanding about leakage in real WDS.

2 LEAKAGE IN WATER SUPPLY SYSTEMS

"In many respects, the map depicting the various issues and processes involved in water distribution systems is a labyrinth."

"...the labyrinth contains numerous processes, sub–processes states of being with their associated causative factors, feedback loops and inter–relationships. Most researchers and planners subconsciously appreciate this multiplicity when they model specific processes or limit their analyses to narrowly defined areas."

Colombo e Karney (2003)

Leakage in WDS is a challenging problem that has calling researchers attention through the years. Many different strategies and methodological approaches has been placed in a way to highlight sustainable solutions for establishing leakage control under distinct hydraulic conditions.

This chapter presents a review on leakage in WDS, first by introducing the main literature methods to deal with leaks; second by focusing in their hydraulic fundamental concepts.

2.1 WATER LOSS IN WDS

In the field of water distribution systems studies, the term *Water loss* refers to volume of water pumped into the system that are unaccounted on end users flow meters and do not return to the water facilities as financial revenue. According to Thornton, Sturm e Kunel (2008), there are two main categories:

- *Real water losses*: Volume of water that have left the system undesirably, including leakage, reservoir overflow, improperly open drains or system blow-offs.
- *Apparent water losses*: Volume of water that have left the system to achieve water demand, not properly accounted in systems database, including underestimated metering, illegal consumption or database handling errors.

In the first category, the increase of flows is relative to practical problems, while the second is summarized by a revenue problem, where the water used is basically not accounted for. In such a context, both problems must be placed by water utilities, but a special attention should be given to the *real water losses*, as potential environmental, health and energy implication (COLOMBO; KARNEY, 2002). Indeed, the *apparent water losses* importance is still remarkable due to their relevance and understanding to improve *real water loss* assessment.

A more detailed definitions about the water balance components is presented in Figure 1, from Alegre et al. (2006). In this methodology the sum of *real* and *apparent* water losses is defined as *nonrevenue water* (NRW). The NRW for a WDS is typically the system input volumes that are not accounted for, thus they are also named *unaccounted-for-water* (ZYL, 2004).

System input volume [m3/year]	Authorised consumption [m3/year]	Billed authorised consumption [m3/year]	Billed metered consumption (including water exported) [m³/year]	Revenue water [m3/year]
			Billed unmetered consumption [m3/year]	
		Unbilled authorised consumption [m3/year]	Unbilled metered consumption [m3/year]	Non-revenue water [m3/year]
			Unbilled unmetered consumption [m3/year]	
	Water losses [m3/year]	Apparent losses [m3/year]	Unauthorised consumption [m3/year]	
			Metering inaccuracies water losses [m3/year]	
		Real losses [m3/year]	Real losses on raw water mains and at the treatment works (if applicable) [m3/year]	
			Leakage on transmission and/or distribution mains [m3/year]	
			Leakage and overflows at transmission and/or distribution storage tanks [m3/year]	
			Leakage on service connections up to the measurement point [m3/year]	

Figure 1 – IWA components of water balance for a WSS
Source: Adapted from (ALEGRE et al., 2006)

A compilation of reported values for NRW from different countries is presented in Table 1, clearly indicating that water losses in WDS is a world problem.

In 2006 the World Bank has estimated a global NRW of 48.6 $billion\, m^3$, of which 67% were *real losses* and 33% were *apparent losses* (THORNTON; STURM; KUNEL, 2008). Accounting for *real water losses*, researchers estimate that the impact represent 35% of total water supplied in the world (Farley et al. 2008, apud XU et al. 2014a). Considering the potential implications for sustainable development, it is required, especially in Brazil (NRW $\approx$ 40%), the adoption of integrated measures for a rational approach and management.

Real water losses, could also be classified regarding its origins, which result in two main categories (adapted from THORNTON; STURM; KUNEL, 2008):

- *Operational causes*: Volume of water lost due to human error in WDS (Reservoir overflow, improperly open drains or system blow-offs), by *expected paths*.

Table 1 – Compilation of reported values for NRW
Source: Colombo e Karney (2002), Zyl (2004), Pertel (2014)

City/Country	**NRW**[a]	**Source**
Europe	9 – 30 %	Lai, 1991
Malaysia	43 %	Lai, 1991
Bangladesh	56 %	Chowdhury, 1999
North America	20 – 50 %	Brothers, 2001
Arequipa, Peru	45 %	WHO, 2001
Haiphong, Vietnam	60 %	WHO, 2001
Jerusalem, Israel	24 %	JWU, 2003
Mutare, Zimbabwe	52 %	Gumbo, 2001
Oshakati, Namibia	40 %	Government of Namibia, 2002
Johannesburg, South Africa	40 %	Sapa, 2003
Brazil	40 %	Pertel (2014)

[a] Nonrenuable water percentage of total system entrance.

- *Leakage*: Volume of water lost through system infrastructure damages (pipe cracks and bursts, failed connections, reservoir holes), through *unexpected paths*

Despite all rational and consistent assessment of WDS, leakage happens and represents the dominant component of NRW (COLOMBO; KARNEY, 2002). In such a context, a strategical effort to manage leakage during system operation is required, specially to guarantee risk management, accountability and system performance.

Leakage in WDS results from a combination of factors associated with operational and construction aspects, that are fundamentally unpredictable. As a matter of fact, leaks can happen since first installation or being result of system parts degradation over years of use without proper maintenance.

In the last century the adoption of high pressurized WDS have intensified leakage and pipes susceptibility to new damages, since maximum pressure acceptance is sometimes violated by rapid transient flows (LAMBERT, 2001). In such context, the existence of leakage in WDS could also contribute to relieve high pressure peaks and prevent pipe bursts (COLOMBO; KARNEY, 2003). Nonetheless, leakage could also be consequence of high mechanical impacts over the soil surrounding the pipes from intensive building activity near the WDS. So far, the most common causes of leakage still need extensive field research in order to confirm the overall hypothesis described above (PUUST et al., 2010).

Individual leaks in WDS could be classified according to their detectability, which is strongly connected with its flow magnitude, and can be summarized as:

- *Reported Leakage/Bursts/Brakes*: Higher leakage flows which are easily detected by water facilities.

- *Unreported Leakage/Detectable Leakage*: Medium leakage flows. Detectability depends on water loss analysis.

- *Background Leakage/Undetectable Leakage*: Low leakage flows. Undetectable by most common technologies.

Intuitively, it is expected that the leak detectability be directly proportional to its magnitude and inversely related to its total duration – time between the leak occurrence and its repair. In majority of WDS leakage detection is made by visual recognition of water in the surface above pipes, which restrict then to deal only with *reported leakage*. In the case of the *unreported leakage* and *background leakage*, greater effort is needed to localize then. Water losses programs have been developed in latest years to reduce detectable leakage in WDS, and also to better quantify water losses impacts over system total costs (THORNTON; STURM; KUNEL, 2008).

Contextualizing the leakage problem in WDS, Colombo e Karney (2003) propose a interpretation of the whole system conception, designed as a *water distribution system labyrinth* (Figure 2). The authors points to the necessity of a comprehensive view of the WDS and have highlighted four main characteristics associated to the water losses problem: system failure, breaks, leaks (detectable and undetectable), energy use and water use.

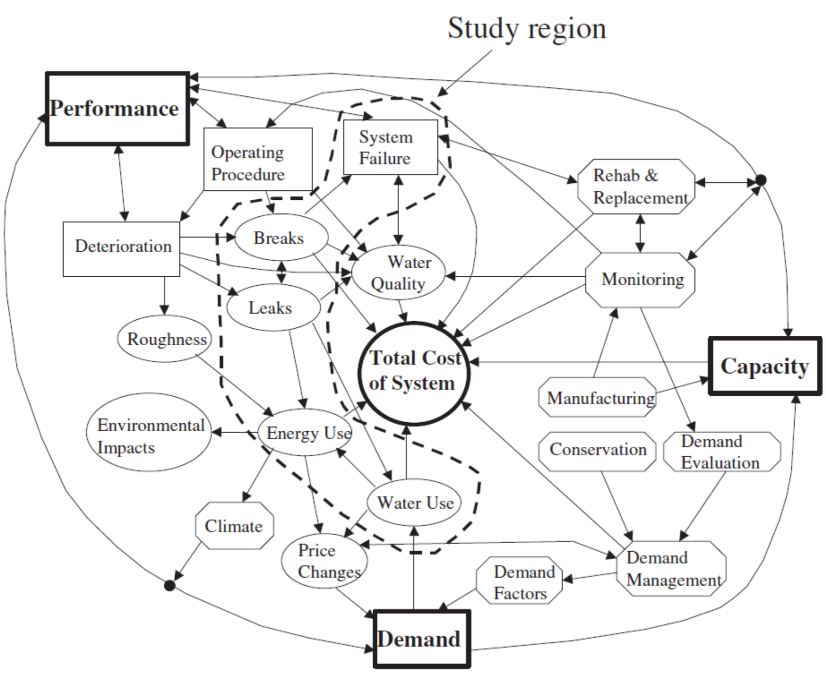

Figure 2 – The water distribution system labyrinth

Source: Colombo e Karney (2003)

The challenge of understanding the overall leakage problems, and developing solutions, consist in integrating information from real networks, comprising: topological aspects, hydraulics dynamics and the demand requests with strong temporal dependence. Furthermore, from a specific point of view of the operation, the knowledge about forms, causes and behavior of leaks in real WDS also restrict the physical understanding of this question.

Therefore, aiming to mitigate the leakage problems, intensive research were developed from several different perspectives to understand and also deal with leaks. In addition, different approaches are also consequence of the diversity of water systems, being relevant to evaluate each system conditions to establish an appropriate leak manage solution (PUUST et al., 2010, CHIS, 2007, COLOMBO; KARNEY, 2002, FERRANTE et al., 2010, SCHWALLER; ZYL, 2015).

Approaches classified as *leak detection techniques* (FERRANTE et al., 2014) are highlighted as the most common strategy for deal with leakage in WDS. They consist of developing tools to find and repair leaks (LIU; KLEINER, 2013). Once the WDS networks are usually underground, detect any damage at the pipes requires special techniques and specialized manpower.

Leak detection techniques are usually based on a two stage analysis, characterized by the accuracy of leakage localization. The first stage is focused on a *rough localization* and must select WDS areas with higher probability of containing leaks, while the second is focus on leakage repair and must precisely evaluate individual leak location.

The use of computational models for simulating the dynamic behavior of water systems is strong on the first step, since they offer the possibility of extended system analysis with available information – e.g. demands, pressures and flows (GOULET; COUTU; SMITH 2013, BEN-MANSOUR et al. 2012, LIJUAN; HONGWEI; HUI 2012, PÉREZ et al. 2011, COLOMBO; KARNEY 2002). Locating leakage with WDS models consists of identifying gaps in networks water balance. The method accuracy depends on the combination of quality data with a set of mathematical equations that properly represent the WDS and leakage behavior.

The second stage is supposed to bridge the gap between the modeling approach results and leaks repairs. Thus, highlights the usage of sensing technology, which aims to acquire and analyze signs of leakage, such as noise and disturb in soil proprieties (CATALDO et al., 2012, PUUST et al., 2010). The precise leak location is essential, since replacement and repair costs are significant. In fact, the costs of a single leak could be lower then the cost for repair it, depending of the *leaking time* (period between the leak starts and be repaired). Hence, not just an accurate leak detection is important, but also a further investigation about leakage costs for the system are required to judge repair priorities (PUUST et al., 2010). Additionally, there are a lot of different sensors for leak detection, because their applicability depends on individual system characteristics – e.g. pipe materials, depth and access, soil proprieties, environmental noise – what can impact in an effective leak detection program (CHIS 2007, LIU; KLEINER 2013).

Despite the great advance of *leak detection* techniques in recent years, their application use is constrained by economical factors and specialized manpower. Hence, trying to mitigate the leakage problem in the absence of tools for direct repair the network damages, another research approach has been widely developed, named *leakage control techniques* (FERRANTE et al., 2014).

The strategy of *leak control* aims to mitigate the leakage problem by indirect actions targeting system pressure management. This strategy complements the *leak detection* approach, because specific changes in system operation conditions could drastically reduce leakage without direct repairing the pipes. Nowadays, it is commonly accepted that reducing operational pressures decrease leakage (ZYL, 2014; LAMBERT, 2001; WALSKI et al., 2009). However, the effectiveness of control methods depends on precise relationships between leak flows and operational pressures.

Therefore, the *leakage control* strategy consists of an optimization problem, subject to find the lowest system pressure without compromising demands. Indeed, these strategies eventually facilitate the *leak detection* appliance by improving the informations about leakage in the WDS (GOULET; COUTU; SMITH, 2013).

Usually, the first step for developing a better leakage control in a WDS consists of estimates its total leakage. This task, could be done by *top-down* approaches – estimates the system leakage through a full water balance, or by *bottom-up* approaches – direct estimations using *minimal night flow* measurements and analysis (THORNTON; STURM; KUNEL, 2008). After estimating systems total leakage, further analyze is required to set up a full diagnose of the system, relating the operational pressures and the leakage flows, integrating the system topology and demand patterns.

Based on system diagnoses, several actions could be proposed to reduce operational pressures and leakage, which will depend on each system configuration. A common measure adopted by water facilities is installing *pressure reducing valves* (PRVs), dividing role system in pressure zones (SCHWALLER; ZYL, 2015; WRIGHT; STOIANOV; PARPAS, 2014; THORNTON; STURM; KUNEL, 2008). This method is suitable for systems influenced by topography, where higher pressures occurs in lower elevations, thus PRVs could prevent the propagation of high pressure, without compromising demand flows in those areas.

Another promising method consists of optimizing system pumping in low demand periods, decreasing system pressures (GIUSTOLISI; LAUCELLI; BERARDI, 2013). In contrast to PRVs, this strategy reduces the system energy consumption, while the first reduces systems pressure by dissipating part of hydraulic energy of the flow. Hence, it is more efficient, but requires higher investment.

Notwithstanding, the development of *leakage control* techniques have also pointed to impacts in WDS *performance*, specially regarding systems *energy use* (COLOMBO; KARNEY, 2002, COLOMBO; KARNEY, 2005, GIUSTOLISI; LAUCELLI; BERARDI, 2013, XU et al., 2014b, CABRERA et al., 2015). Leakages directly dissipate a part of the system hydraulic energy, which is embedded in water loss, but also increase friction losses in the paths between water intake and each leak location (COLOMBO; KARNEY, 2002). Nonetheless, they also impact pumping performance and the role of system hydraulics, since water demands are increased (COLOMBO; KARNEY, 2005).

Once WDS requires lot of energy for transporting water, an important task is to evaluate *energy losses*, in order to quantify the real costs of leakage to WDS, which are beyond the water loss costs. Therefore, an energy audit must be performed, integrating every input and output of hydraulic energy in all network (CABRERA et al., 2010). However, since each system has its own characteristics, defining and analyzing the *energy efficiency* from a WDS is not simple. A possible solution is presented in Cabrera et al. (2015), where the authors propose the comparison between the *real system*, an *ideal system* (without water losses) and an *achievable system* (*real system* with mitigating actions). The strategy aims to link possible action measures to specific causes of energy losses, which could improve significantly the WDS maintenance. However, such analysis requires a complete set of information regarding the system behavior, comprising topology, hydraulic and electric aspects, thus is a hard effort.

A full description regarding energy efficiency impacts from leakage in WDS means to know what type of leaks are affecting more the system behavior and which are the maintenance priorities to deal with them. Such information would definitely improve the WDS performance, enhancing the use of the water and energy by the water facilities. Furthermore, this effort could also improve the attention given to the leakage problem, since energy loss quantification have not been properly addressed in the literature (COLOMBO; KARNEY, 2005).

2.2 LEAK HYDRAULICS

The previous section have introduced the leakage problem in WDS, highlighting several methods to asses its impacts. This section, aims to explore the basic hydraulic fundamentals of leakage in WDS.

A comprehensive approach about leak hydraulics consists of understanding the fluid behavior in the leakage neighborhood and establishing relationships between pipe flow and leakage variables. However, the great diversity of conditions in addition to many leak formats and sizes have prevented a better assessment of leak hydraulics so far, and still has been focus of intensive research (ZYL; CLAYTON, 2007; CASSA; ZYL; LAUBSCHER, 2010; FERRANTE et al., 2014; SCHWALLER; ZYL, 2015)

In a WDS, leakage can occur in *pipe sections* or *system nodes*, wherein second category comprises several system components (e.g. joints, connections, valves). However, since pipe sections are the most abundant system component (MAYS, 2000), research on the field usually neglects the leakage occurrence in system nodes (GREYVENSTEIN; ZYL, 2007, WALSKI et al., 2009, BEN-MANSOUR et al., 2012, FERRANTE et al., 2014). Additionally, once WDS transports drinkable water with smooth changes in system flows, for modeling leakage is commonly assumed constant water density ρ and steady flows.

Leaks hydraulic characteristics are basically determined by the *internal* and *external* pipe conditions allied to the leak shape. Figure 3 presents an overall scheme of a leaking pipe stretch, highlighting the main variables involved in the phenomenon, where A_{up} = upstream cross section pipe area, A_{down} = downstream cross section pipe area, $A_{orifice}$ = orifice area, A_{VC} = vena contracta area, Q_{up} = upstream flow, Q_{down} = downstream flow, Q_{leak} = leakage flow, h_{up} = upstream pipe pressure head, h_{ext} = external pressure head, W_{pipe} = pipe wall thickness, D_{pipe} = pipe internal diameter, $D_{orifice}$ = orifice diameter, V_{up} = average flow velocity upstream, V_{down} = average flow velocity downstream, V_{leak} = average leakage flow velocity, E_{up} = energy flux upstream, E_{down} = energy flux downstream, E_{leak} = leakage energy flux, E_{diss} = dissipated energy flux and g = gravitational acceleration. In the scheme, a control volume is defined by the upstream and downstream surfaces, the pipe wall and a projection from the orifice to the vena contracta surface.

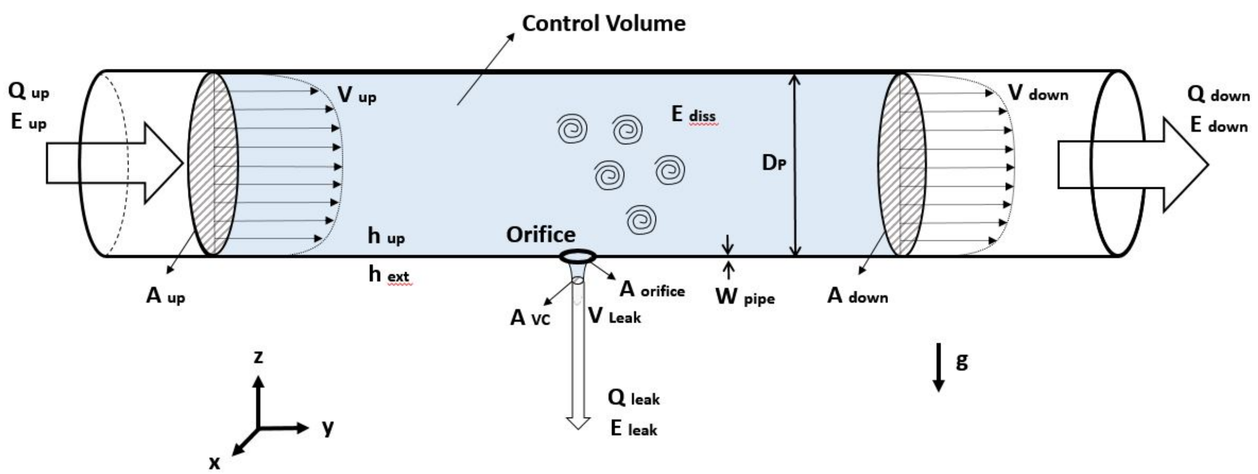

Figure 3 – Leak representation through a round orifice in a pipe wall

The mass balance for the control volume with previous assumptions can be estimated by the equation of mass conservation (Equation 2.1), resulting in the mass balance for the leakage phenomenon (Equation 2.4).

$$\frac{\partial \rho}{\partial t} + \nabla . \left(\rho \vec{V}(\vec{x}, t) \right) = 0 \tag{2.1}$$

$$Q = A\,V \tag{2.2}$$

$$V = \int \vec{u}\, dA \tag{2.3}$$

$$Q_{up} = Q_{down} + Q_{leak} \tag{2.4}$$

A scheme for the streamlines is also presented in Figure 4, highlighting a hypothetical fluid path for a leakage phenomenon. At indicated control surfaces, the streamlines are parallel highlighting no accelerations of fluid particles, this hydrostatics conditions allowing to apply a stream tube approach. Moreover, changes in streamlines directions disturbs the flow velocity profile, which results in the dissipation of energy due to instant friction (E_{diss}) – transformation of kinetic energy in heat. The dissipation of energy caused by the leak is similar to *local head losses* caused by valves or curves in WDS, as consequence of transformations of kinetic energy to heat.

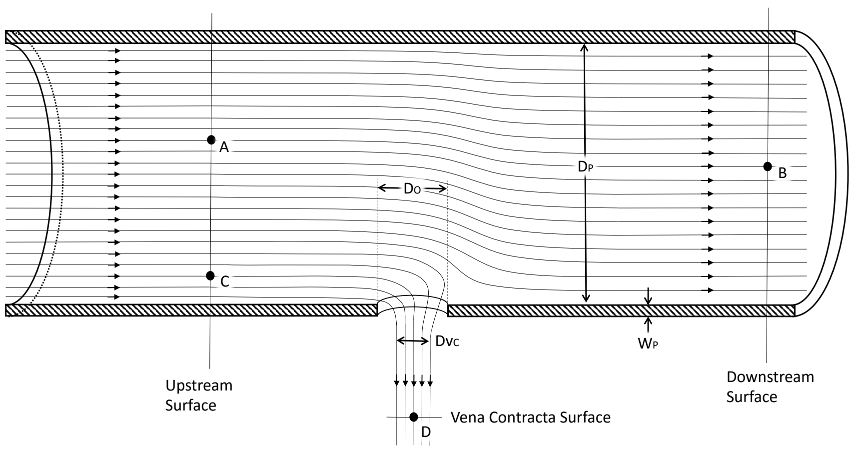

Figure 4 – Scheme of flow streamlines for a leaking trhough a round orifice in a pipe wall

Notice that in the case of the leakage pipe stretch being buried in a solid medium, the exit of the leakage flow will be disturbed, since would exists a flow resistance outside the pipe. The presented scheme is valid just for a non solid homogeneous medium surrounding the pipe, where the high kinetic energy of the leakage flux can be dissipated smoothly.

In sequence, two traditional approaches regarding the leakage hydraulics are better detailed: individual leakage flow estimations and relationships between leakage and WDS energy use.

2.2.1 Inidividual Leakage Flow Estimation

The basis for developing strategies to reduce *real water losses* is the main goal of leakage flow estimation. In such context, to establish direct relationship between the pipe and leakage flows, it is commonly adopted the use of Bernoulli's theorem for a steady, irrotational and barotropic flow (constant density, isothermal and isentropic), derived from the physical principles of energy and mass conservation (KUNDU; COHEN; DOWLING, 2012).

Bernoulli's theorem establish that for a irrotational barotropic flow the energy grade line must have constant values for the flow streamlines, summarized by Equation 2.5, where $h\,(m)$ = pressure head, $\vec{u}\,(m/s)$ = velocity vector and $z\,(m)$ = elevation, of a fluid element in a streamline.

$$h + \frac{|\vec{u}|^2}{2g} + z = constant \tag{2.5}$$

Thus, assuming the barotropic flow condition and applying Bernoulli's equation (Equation 2.5) for the leakage streamlines, between points C and D in Figure 4, is possible to establish a relationship between the pipe's and leakage flow – Equation 2.6.

$$h_C + \frac{|\vec{u_C}|^2}{2g} + z_C = h_D + \frac{|\vec{u_D}|^2}{2g} + z_D \tag{2.6}$$

Considering $h_C = h_{up}$, $h_D = h_{ext}$ (discharge for atmosphere) and $z_C \approx z_D$, results in the Equation 2.7, which establish the velocity of the leakage flow as function of the pipe pressure head and velocity.

$$|\vec{u_D}| = \sqrt{2g\,(h_{up} - h_{ext}) + |\vec{u_C}|^2} \tag{2.7}$$

Assuming that pipe's flow kinetic energy could be neglected ($2g\,h_{up} >> |\vec{u_C}|^2$), that $|\vec{u_D}| \approx V_{orifice}$ (average flow velocity through the orifice) and that $\Delta h_{orifice} = h_{up} - h_{ext}$, results in the known Torricelli's equation (IDELCHIK, 2003) – Equation 2.8.

$$V_{orifice} = \sqrt{2g\,\Delta h_{orifice}} \tag{2.8}$$

Hence, the leakage flow could be estimated by the product of the orifice velocity (Equation 2.8) by the flow cross-section area. However, the flow through orifices with sudden pressure variation is characterized by a streamlines contraction after the orifice, due the fluids viscosity and the Newton's first law of motion, thus implying in a minimal cross-section area (A_{VC}) smaller then the orifice area ($A_{orifice}$). In this context, the vena contracta area (A_{VC}) could be estimated by the product of orifice area ($A_{orifice}$) and the contraction coefficient (ϵ), which comprise the flow contraction – Equation 2.9 (IDELCHIK, 2003).

$$A_{VC} = \epsilon\, A_{orifice} \tag{2.9}$$

Additionally, the flow contraction in the orifice is also characterized by a fluid resistance due to viscosity forces, which are commonly accounted by the *velocity coefficient* ϕ – Equation 2.10, where ξ_0 = *coefficient of fluid resistance* (IDELCHIK, 2003).

$$\phi = \frac{1}{\epsilon\, \sqrt{\xi_0}} \tag{2.10}$$

Therefore, by the product of the orifice average velocity (Equation 2.8) and the contraction and velocity coefficients (Equations 2.9 and 2.10), the leakage flow (Q_{leak}) could be estimated by the equation 2.11 – the *orifice equation*, where C_d = discharge coefficient (Equation 2.12). The discharge coefficient has been widely studied for most common orifices forms, resulting in several functions to estimate the parameter for distinct conditions (IDELCHIK, 2003).

$$Q_{leak} = \epsilon\, \phi\, A_{orifice}\, V_{orifice} = C_d\, A_{orifice}\, \sqrt{2g\, \Delta h_{orifice}} \tag{2.11}$$

$$C_d = \phi\, \epsilon \tag{2.12}$$

Traditionally, leakage analysis in WDS have been simplified to flow through round orifices in the pipe walls open to atmosphere, based on the orifice equation (GREYVENSTEIN; ZYL, 2007, CASSA; ZYL; LAUBSCHER, 2010, FERRANTE et al., 2014, FRANCHINI; LANZA, 2014, ZYL, 2014). This approach comprises the simplest shape for leakage shapes in WDS, and could provide a basis for further investigation on more complex leak forms.

Further investigation about the velocity and contraction coefficients demonstrates that both parameters are closely linked to the orifice shape characteristics, and could also vary according to flow regime behavior (IDELCHIK, 2003). The flow regime is commonly defined by the rate of turbulence in the flow. Usually, the Reynolds Number – *Re* is used to quantify such effects, function of $\rho (kg/m^3)$ = fluid density, $V(m/s)$ = average flow velocity, $L(m)$ = characteristic length and $\mu (N.s/m^2)$ = is the dynamic fluid viscosity. Two *Re* numbers have been considered for studied leakage in WDS (Equation 2.13).

$$Re_{leak} = \frac{\rho\, V_{leak}\, D_{orifice}}{\mu_{water}} \qquad\qquad Re_{pipe} = \frac{\rho\, V_{up}\, D_{pipe}}{\mu_{water}} \tag{2.13}$$

For many orifice shapes are expected transitional flow regimes with $Re_{leak} \in [10, 10^5]$, and turbulent flow for upper values. In most situations C_d has a strong dependence on leakage Reynolds number (Re_{leak}) for transitional regimes, being also a function of pipes flow Reynolds number (Re_{pipe}), cross-sectional areas proportions (orifice and pipes areas) and other orifice characteristics, such as: wall thickness, edge types, diameter and others (IDELCHIK, 2003).

Illustrating the behavior of ϕ, ϵ and C_d according to leakage Reynolds number (Re_{leak}), a chart from Idelchik (2003) presents an example of coefficients behavior for an orifice in a thin wall (Figure 5). For small Reynolds numbers ($Re_{leak} \leq 10$), the velocity coefficient ϕ induce low C_d values (for $Re_{leak} \leq 10$, $C_d \approx \phi$), hence the viscosity forces govern the orifice flow, and consequently, the fluid mechanical energy losses are higher. In the case of higher Reynolds numbers ($Re_{leak} > 10^5$), which characterize turbulent flow regime, the coefficient behavior usually becomes stable ($C_d \approx 0.6$).

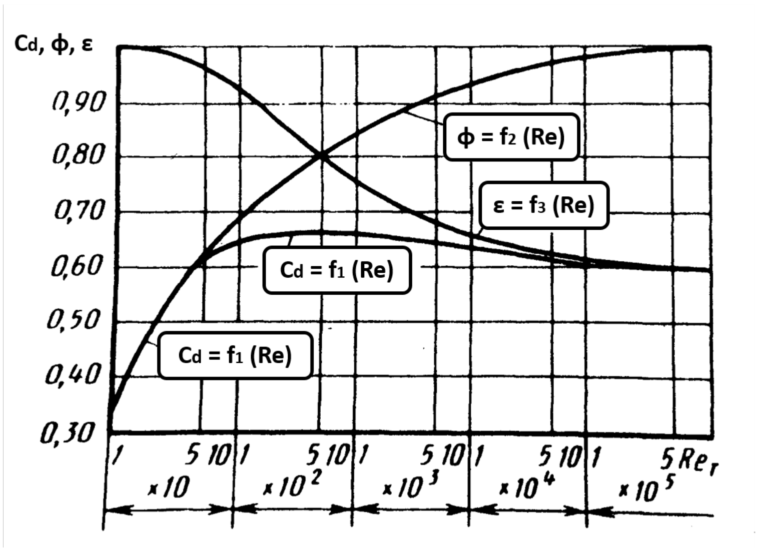

Figure 5 – Discharge coefficient C_d, Velocity coefficient ϕ and jet contraction coefficient ϵ plotted against Reynolds number Re for a thin wall orifice flow

Source: Adapted from Idelchik (2003)

For modeling leakage with the Torricelli's equation (Equation 2.11) the discharge coefficient is normally adopted by constant values in the range from 0.5 – 0.7, as considering leakage turbulent flow condition (FRANCHINI; LANZA, 2014, FERRANTE et al., 2010). However, Lambert (2001) and Zyl e Clayton (2007) had shown that values of C_d could significantly vary for leakage in WDS, and after Schwaller e Zyl (2015) propose that C_d is also affected by leak shape, pipe material and pipe curvature. Therefore, the adoption of a fixed C_d could cause significant errors in flow calculation.

Leakage in WDS is a physical phenomenon with distinct physical characteristics from common flows through orifices studied in fluid mechanics. The reason is related to the behavior of the streamlines that are initially constrained in the pipe flow and are forced to rapidly change direction, while flow majority remains in the pipe (Figure 4). Thus, a leakage phenomenon through an orifice is not properly represented for common studies, and its hydraulic behavior will hardly be accurately explained by the *orifice equation* and literature coefficients (IDELCHIK, 2003).

The application of the orifice equation (Equation 2.11) for modeling leakage in WDS had shown high errors and inaccuracy for estimating leakage flows. Therefore, researchers have proposed the empirical *power equation* (Equation 2.14), where a pressure head exponent is a new *adjustment parameter*, the exponent coefficient $N1$, and the other equation terms were compiled in the coefficient C (SCHWALLER; ZYL 2015, ZYL 2014, ZYL; CASSA 2014, FERRANTE; MENICONI; BRUNONE 2014, WALSKI et al. 2009, ZYL; CLAYTON 2007, LAMBERT 2001).

$$Q_{leak} = C\, h^{N1} \tag{2.14}$$

In order to improve the physical understanding of the power equation components, the *complete power equation* was considered (Equation 2.15). Hence, is important to observe that the discharge coefficient C_d from the *orifice equation* was changed by a new leakage coefficient C_L, because *this parameter does not have the original physical meaning of C_d*, unless in the case of $N1 = 0.5$, thus its a new adjustment parameter.

$$Q_{leak} = A_{orifice}\, C_L\, \left(2g\, (h_{pipe} - h_{ext})\right)^{N1} \tag{2.15}$$

The use of the power equation (2.14) has become very popular due to its simplicity and better results in comparison to the orifice equation. Indeed, the equation use is recommended by several authors, including IWA *Water Loss Task Force* (THORNTON; STURM; KUNEL, 2008). However, studies about $N1$ indicate that the exponent could change in a wide range, from 0.41 to 2.79, for different leak forms or multiple leaks in complex water systems. In the Figure 6 from Walski et al. (2009), its presented a compilation of studies from 1979 to 2007, reporting values of leak power $N1$ for many conditions and crack forms.

In general, studies about the power equation have shown that its usage with constant parameters is not enough to represent leakage on WDS (SCHWALLER; ZYL, 2015). In fact, C and $N1$ include all complexity from the leakage phenomenon, such as the flow regimes, material behavior and soil hydraulic influence. Thus, it is not surprising that trying set constant values to both parameters will result in inaccurate leakage flow estimations under different WDS conditions.

Reference	Values	Conditions
Ogura (1979)	1.39-1.72	Slits
Hikki (1981)	0.5	Drilled holes
May (1994)	0.5 fixed area 1.5 size = f(P) 2.5 long	Fixed area Size = f(Pressure) Longitudinal
Lambert (2001)	0.52-2.79	Literature
Farley and Throw (2003)	0.70-1.68 0.63-2.12 0.52-2.79	UK (1977) Japan (1979) Brazil (1999)
Thornton and Lambert (2005)	0.5-1.6	Function of ILI
Walski et al. (2006)	0.66-0.76	Drilled holes
Greyvenstein and VanZyl (2007)	0.52 1.38-1.85 0.79-1.04 0.41-0.53 0.67-2.3	Round Hole Longitudinal PVC Longitudinal AC Circumferential Corrosion steel
Noack and Ullanicki (2007)	0.5 – 1.0	f(soil permeability)

Figure 6 – Reported N1 values

Source: Walski et al. (2009)

In addition, the relationship between the power equation (Equation 2.14) and the orifice equation (Equation 2.11) could be misunderstanding, because changes in exponent of pressure head term from 0.5 to an arbitrary parameter affects the equation dimensional balance. Thus, for each distinct value of $N1$, the leakage coefficient C assumes a new physical dimension, and also a new physical meaning.

From a practical point of view, the power equation has provided a better solution to estimate leakage flows in WDS. However, by suppressing the phenomenon complexity in two coefficients it has also prevented further understanding about leakage hydraulics. In this context, trying to explain the wide range of the power equation coefficients, researchers have advanced investigations about pipes elasticity and soil hydraulic influence as part of physical influences in leakage phenomenon (ZYL; CLAYTON, 2007, CASSA; ZYL; LAUBSCHER, 2010, SCHWALLER; ZYL, 2015).

In the last five years, research have focused on pipes elasticity, presenting several experimental data analysis that justified physically $N1 \neq 0.5$ (CASSA; ZYL; LAUBSCHER 2010, ZYL 2014, SCHWALLER; ZYL 2015 and ZYL; CASSA 2014). These papers, are based in the *Fixed and Variable Areas* (FAVAD) concept, proposed by May 1994, apud Cassa, Zyl e Laubscher (2010), where some leaks have *variable areas*. Thus, the *real leakage area* $A^*_{orifice}$ is estimated by Equation 2.16, where $A_{orifice}$ = original leakage area (unpressurized pipes) and m = area slope coefficient (m is closely linked to leak forms, pipe material mechanical characteristics and soil external forces). Additionally, Cassa, Zyl e Laubscher (2010) proved that all leaks in WDS have elastic behavior, but even considering distinct variables, the FAVAD concept is valid.

$$A^*_{orifice} = A_{orifice} + m\, h_{pipe} \tag{2.16}$$

The insertion of FAVAD concept in the orifice equation (Equation 2.11), lead to the *FAVAD equation* (Equation 2.17). Although the new equation development is based on physical concepts (in contrast to the power equation), it is still limited to explain leakage flow dependences to pressure head exponents up to 1.5, while literature reports values up to 2.79.

$$Q_{leak} = C_d\, \sqrt{2g}\, (A_{orifice}\, h^{0.5} + m\, h^{1.5}) \tag{2.17}$$

In addition to the *pipe material behavior*, the influence of *soil hydraulics* on leakage phenomenon appears to be as important as previous analysis, which have assumed leakage discharge to external atmospheric pressure. The soil surrouding pipes could prevent the free flow of the leakage volume of water, what could influence in pipe's external pressure (h_{ext}), decreasing the pressure head drop in the leakage. Research has shown that soil hydraulics can act as flow control in some leakage conditions, establishing different relationships between leakage flow and system pressure than the orifice and power equations, and must be taken into account (Walski et al. 2004, Guo et al. 2013).

In Guo et al. (2013) a two dimensional analysis of leakage flow through longitudinal cracks was developed focusing in the soil hydraulic conductivity. The authors have established a linear relationship between leak flow and pipe pressure head, strongly influenced by soil conductivity. Main research results showed that leakage flows could be calculated by equation 2.18 based on the *Darcy Law* for fluid motion in porous media (GUO et al., 2013), where K = soil conductivity, h = pipe pressure head and C^* = leakage position coefficient, which depends on pipe depth and leak shape characteristics.

$$Q_{leak} = C^*\, K\, h \tag{2.18}$$

The soil hydraulic influence proposed by Guo et al. (2013) was experimentally tested, but only low pressure head levels were analyzed (up to $10\,m$). In contrast, the great majority of WDS operates at higher pressure levels, thus higher leakage velocities are expected, which leads to greater probabilities of soil erosion in leakage neighborhood. Therefore, leakage would occur more likely as the pipe was submerged in the water than in soil, and further soil hydraulic influence would still affect the flow, but in distinct rates (depending on the final surrounding soil geometry configuration).

In summary, the main factors associated with *individual leakage flow* estimations, pointed out by literature, consist of the *system pressure*, the *pipe material behavior* and the *soil hydraulic influence*. However, further investigations is required in order to gather all factors in a single equation for estimating accurately the leakage flows in WDS, or establish the conditions and limitations of each equation. Furthermore, from a practical point of view, the study of individual leak hydraulics in real WDS is still challenging, since several analysis comprise all systems leakage, with multiple leaks in different locations. About these efforts, the influence of system dynamics and demand patterns, can lead to imprecise conclusions about individual leak hydraulics. Hence, better data acquisition about leakage in real systems must be performed in order to confirm their behavior and improve leakage flow estimates.

2.2.2 Leakage & WDS Energy Use

Beyond the water loss, leakage in WDS also causes energy losses, since the water is the system *energy carrier* (CABRERA et al., 2014). Hence, if the water leaves the system so does the energy, but unfortunately the increase of system flows by leakage also implies in other indirect sources of inefficiency (COLOMBO; KARNEY, 2003).

The use of energy in WDS depends on every system components, being the leakage just one source of inefficiency (CABRERA et al., 2010). However, since leakage increase the total volume of water transported in the system, all energy losses addressed to the leakage flows, while in the pipes, can be understood as *leakage energy losses* (COLOMBO; KARNEY, 2002, COLOMBO; KARNEY, 2005, CABRERA et al.,2014).

In such a context, the only way to precisely quantify all energy losses associated to leakage is by modeling the real system behavior (with leaks) against the same system under ideal conditions (without leaks) (CABRERA et al., 2015). However, such analysis could just provide a leakage energy loss indicator relative to the original system conception. Thus, the leakage energy losses are linked to all system optimization and could depend more on WDS characteristics then the individual leak hydraulics.

On the other hand, understanding the energy losses caused by leakage in WDS could improve system maintenance, by choosing most impactful leaks. Therefore, this section aims to explore the relationship between leakage and tree basic forms of energy losses in WDS: *energy loss embedded in water*, *local head losses* and *continuum head losses* (MAYS, 2000).

Initially the local leakage energy losses will be prospected, which are composed by the energy dissipated by friction at the leak point (E_{diss}) and the embedded energy of the leakage flow: the leakage hydraulic energy (E_{leak}). Thus, to quantify the leakage energy losses it is necessary to estimate flow conditions in the leakage neighborhood, and perform a full energy balance for the control volume in Figure 3.

Therefore, by applying the Bernoulli's equation (Equation 2.5) between points

A (upstream) and B (downstream) in the streamlines scheme of Figure 4, its possible to estimate downstream flow conditions – Equation 2.19.

$$h_A + \frac{|\vec{u_A}|^2}{2g} + z_A = h_B + \frac{|\vec{u_B}|^2}{2g} + z_B \tag{2.19}$$

Considering in equation 2.19: $z_A = z_B$, $A_{pipe} = A_{up} = A_{down}$, the average velocities in both sections (Equations 2.20 and 2.21), and the mass balance equation (Equation 2.1); results in the total pressure head drop in the pipe caused by the leakage ($\Delta h_{pipe} = h_A - h_B$) – Equation 2.22.

$$|\vec{u_A}| \approx V_{up} = Q_{up}/A_{pipe} \tag{2.20}$$

$$|\vec{u_B}| \approx V_{down} = Q_{down}/A_{pipe} \tag{2.21}$$

$$\Delta h_{pipe} = \frac{Q_{leak}\,(Q_{leak} - 2Q_{up})}{2g\,A_{pipe}^2} \tag{2.22}$$

The Equation 2.22 shows that the pressure head inside the pipe will aways be greater downstream the leakage (negative pressure head drop values), since $Q_{leak} \leq 2Q_{up}$. The result is consequence of the decrease in kinetic flow energy due to the reduction of mass inside the pipe, hence part of the kinetic flow energy is transfered to the *potency pressure energy*.

It is important to notice that Equation 2.22 does not account for energy dissipation by friction. Thus, to obtain the real pressure drop in the pipe it is necessary to add a term representing the dissipated energy – h_f – Equation 2.23. Thus, since hf_{diss} exists and it is aways positive (will cause positive pressure head drop), the total pressure head drop could be positive as well, and will depend on the rate of disturb in pipe flow velocity profile.

$$\Delta h_{pipe} = \frac{Q_{leak}\,(Q_{leak} - 2Q_{up})}{2g\,A_{pipe}^2} + h_f \tag{2.23}$$

Once pressures and flows are known in all control surfaces, it is possible to estimate the energy balance in the control volume, which is composed by the mechanical flow energy and the dissipated energy, represented by Equation 2.24.

$$E_{up} = E_{down} + E_{leak} + E_{diss} \tag{2.24}$$

The energy flux for the upstream, downstream and leakage sections are then estimated by equations 2.25, 2.26 and 2.27, respectively, where A_{leak} is the leakage effective area (comprising effects of pipes elasticity and flow compressibility). In this equation the gravity potential energy is neglected, and in consequence of barotropic flow assumption, no changes in fluid internal energy were considered, and all mechanical energy are simplified to kinetic and pressure forms.

$$E_{up} = \rho g Q_{up}(h_{up} + \frac{V_{up}^2}{2g}) = \rho g Q_{up} h_{up} + \frac{\rho g Q_{up}^3}{2A_{pipe}^2} \tag{2.25}$$

$$E_{down} = \rho g Q_{down}(h_{down} + \frac{V_{down}^2}{2g}) = \rho g Q_{down} h_{down} + \frac{\rho g Q_{down}^3}{2A_{pipe}^2} \tag{2.26}$$

$$E_{leak} = \rho g Q_{leak}(h_{ext} + \frac{V_{leak}^2}{2g}) = \rho g Q_{leak} h_{leak} + \frac{\rho g Q_{leak}^3}{2A_{leak}^2} \tag{2.27}$$

The total leakage impact in pipe flow hydraulic power (ΔE_{pipe}) is the sum of the leakage hydraulic power E_{leak} and the dissipated power E_{diss} – Equation 2.28. Furthermore, the decrease in pipe's energy caused by an individual leakage, corresponds to an increase of required power to supply the WDS. Hence, their costs to water facilities could be estimated based in the pumping delivered hydraulic energy.

$$\Delta E_{pipe} = E_{up} - E_{down} = E_{leak} + E_{diss} \tag{2.28}$$

In contrast to the local energy dissipated by leakage, the increase of system flows by leakage will impact mainly in higher friction head losses (COLOMBO; KARNEY, 2002). Since pumped flows are larger, the average flow velocity in the whole system is higher, increasing energy losses due to friction at pipe walls. This energy loss is associated to the increase of system flow by leakage, defined here as *leakage continue head losses*.

Continue head losses are intrinsic of WDS and could be estimated by *Darcy-Weisbach* equation (Equation 2.29), where h_f = head loss cause by friction, f = dimensionless friction factor, L = pipe length, D = pipe diameter, V = mean flow velocity and g = gravity acceleration (MAYS, 2000).

$$h_f = f \frac{L}{D} \frac{V^2}{2g} \tag{2.29}$$

Once the physical reason for the increase of leakage continue energy losses are the higher velocity flows in system pipes, system sectors downstream the leaks preserve their "ideal average velocity". Thus, the leakage continuum energy losses depends on individual leak locations, and will have a linear relationship with the leaks distance to the water sources (COLOMBO; KARNEY, 2002).

Considering the Darcy-Weisbach equation (Equation 2.29) it is possible to estimate the total power dissipation (energy flux) by continuum head losses – E_f, by Equation 2.30, where i = pípe stretch index, N = total of system pipes, f_i = pipe friction factor, L_i = pipe length, D_i = pipe diameter, A_i = pipe cross-section area, Q_i = pipe flow demand part and Q_{leak} = pipe flow leakage part.

$$E_f = \frac{\rho g}{2g} \sum_{i=1}^{N} \frac{f_i\, L_i\, (Q_i + Q_{leak})^3}{D_i\, A_i} \tag{2.30}$$

Therefore, subtracting the power dissipation for an ideal system ($Q_{leak} = 0$), it is possible to establish an an analytical relationship for the leakage continuum head losses power dissipation E_f^{leak} – Equation 2.31.

$$E_f^{leakage} = \frac{\rho g}{2g} \sum_{i=1}^{N} \frac{f_i\, L_i}{D_i\, A_i} \left(Q_{leak}^3 + 3Q_{leak}^2 Q_i + 3Q_{leak} Q_i^2\right) \tag{2.31}$$

The relationships shown above demonstrate that leakage associated energy losses can increase rapidly according to leakage flows. However, stands out that the local and continue head losses do not exhaust the forms of leakage impacts over system energy use. Leakage flows can also affect other component behaviors, such as the performance of hydraulic pumps, that influence the whole system performance.

2.3 SUMMARY OF THE CHAPTER

Leakage is a source of great inefficiency in WDS, by wasting water and energy in the transport of water, and the challenge to deal with them comprises the systems complexity and a wide range of possible leak shapes, locations and magnitudes. Several efforts have been made to develop tools to mitigate leakages in WDS. However, such techniques were still inaccurate, mainly because the leak hydraulics are not properly represented in distinct WDS conditions. Therefore, the advance of leakage understanding requires further investigation about their hydraulic behavior. In addition, further efforts are needed to estimate leakage associated energy losses, which represents part of the leakage costs for WDS and are usually neglected.

3 EXPERIMENTAL APPROACHES IN LEAKAGE SIMULATION

"Experimenters are the shock troops of science."
Max Planck – "The Meaning and Limits of Exact Science" (1949)

Since leakage in WDS is a challenging hydraulic problem, researchers have developed experimental facilities to reproduce their behavior under a controlled and monitored environment, to understand its mechanics. In this chapter the main experimental efforts about leaks in WDS are presented. Such methods have motivated a new experimental setup, developed to investigate leaks in order to establish its influence over system energy efficiency.

3.1 PREVIOUS EXPERIMENTAL RESULTS

Although experimental approaches on leakage research can be unusual, their hydraulic results have a remarkable importance to confirm the wide theoretical development. Furthermore, the main motivation is the challenge of improving the relationship between system pressure and leakage flow, by testing several leak shapes under different operational conditions.

The consolidation of an experimental facility to monitor controlled leakage in a pressurized system appears to be a simple task. Usually, leaks are "produced" by direct drilling or machining in a pipe wall, which are then tested under common operational pressure conditions. Moreover, flow and pressure sensors are used to acquire data from the system, to establish a characteristic curve of *leakage flow vs. system pressure*.

On the other hand, the goal to associate laboratory results to real system conditions still highlights the overall search of better physical understanding of leaks. Once most laboratory facilities have a scale influence in comparison to WDS, precisely reproducing real leakage conditions is a hard task. Therefore, the experimental details play a key role to achieve applicability, and must be carefully planned to improve real leakage understandings.

In this context, the main questions to build a leakage experiment are the characteristics which should be tested, such as: leakage flow, leak area, system pressure head, leak type (shape) and pipe material. Literature reports (Table 2) laboratory conditions also presented in WDS, as system pressure head conditions and common pipe materials. In contrast, individual leak flows, areas and shapes are not easily known from real systems, making it difficult defining the leak characteristics to be tested in laboratory. However, the longitudinal shape appears to be preferred, what could be justified by the more frequently occurrence of longitudinal cracks in pipes, due to perpendicular force of pressure in pipe walls.

Table 2 – Characteristics of Leakage Experiments

Source	**Leakage Flow** (m^3/h)	**Pressure Head** (m)	**Leak Area** (mm^2)	**Leak Type**	**Pipe Material**
Ferrante et al. (2014)	3–11	5–50	50-120	Longitudinal	Steel
Ferrante et al. (2010)	14–36	5-55	180	Longitudinal	Steel, PVC
Walski et al. (2009)	2.8	5-55	25-150	Longitudinal, Circumferential, Round Orifices	PVC
Greyvenstein e Zyl (2007)	12.6 *	2–15 *	– *	Failed Pipes	Steel, Asbestos Cement

* Not precisely reported.

Beyond the system overall characteristics, the leakage behavior could be also affected by the WDS dynamics (turbulence and small fluctuations due to network complexity) and the internal pipes velocity profile. The first will be singular for each WDS, thus its very difficult to be reproduced under experimental conditions. However, some experimental setups could better reproduce system dynamics, Greyvenstein e Zyl (2007) and Walski et al. (2009) have supplied their laboratory systems with direct connections to WDS, adding a control valve to vary the leaking pipe conditions. The same element is not present when the experiment is supplied by a stable pressure head, which is the case of Ferrante et al. (2014) and Ferrante et al. (2010).

Greyvenstein e Zyl (2007) and Walski et al. (2009) also have performed leaks in pipe ends, where all system flow were equal to leakage flow, what is unexpected to happen since the majority of flow probably remains in the WDS pipes downstream the leakage. In Franchini e Lanza (2014), Ferrante et al. (2014) and Ferrante et al. (2010) studies, the leakage was performed in the middle of a specific pipe stretch, in order to better reproduce the pipe velocity profile to be expected in real cases.

Mainly experiments also discharge the leakage direct to atmosphere, neglecting possible effects of pipes surrounding soil in real WDS. This theme has been the focus of previous research (WALSKI et al., 2009, GUO et al., 2013), which concluded that the leakage flow in soil surrounding pipes could affect the pressure drop at the pipe exit, reducing leakage flows. In addition, Bailey e Zyl (2015) have also shown effects of soil fluidisation due to leak jets, which could also influence leak hydraulics and change surrounding soil by erosion processes.

In summary, leakage experiments are inconclusive, and do not cover all possible leakage shapes and conditions that could happen in real systems. It is interesting notice that despite of laboratory setups be very heterogeneous, more experimental research on leakage is needed to confirm hypothesis and improve the knowledge on the field of leaks hydraulic characteristics in WDS.

3.2 THESIS EXPERIMENTAL SETUP

In order to analyze leakage hydraulic relationships between an individual leak and the system energy use, a new leakage experiment was designed and assembled. In previous experimental research no relationships were found regarding the energy dissipation by leakage. Moreover, the leakage experiments in this research have also allowed a more detailed study concerning the leakage hydraulics for round orifices.

3.2.1 The LENHS laboratory at the UFPR

The experiments were performed in the *Laboratory of Energy and Hydraulic Efficiency in Sanitation*, from the *Universidade Federal do Paraná* (LENHS UFPR, 2014 - Figure 7). The choice of LENHS UFPR was based on the laboratory conditions to simulate a WDS with a good control of system behavior, since it offers adjustable pipe networks, hydraulic pumps with speed control, many pressure and flow sensors, control valves and a programmable logic controller (PLC), which is responsible for data acquisition and control.

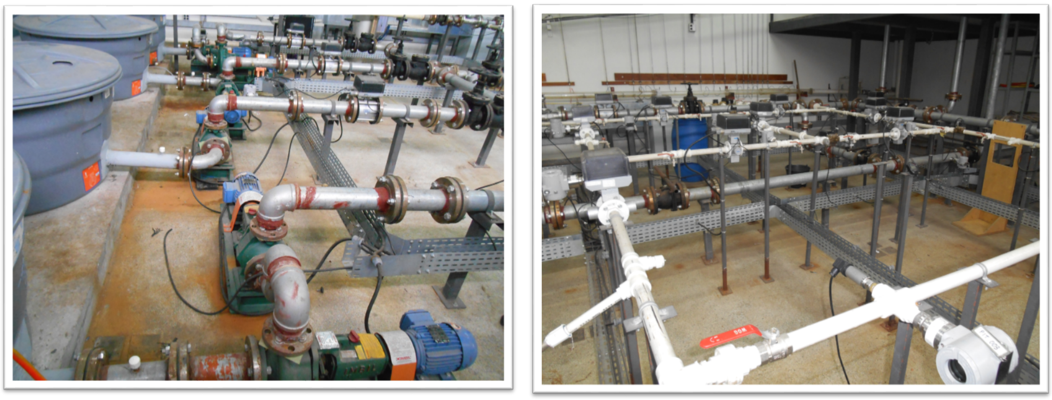

Figure 7 – The Laboratory of Energy and Hydraulic Efficiency in Sanitation – LENHS UFPR, 2014.

The experimental network is composed of galvanized steel pipes with 3″ diameter to simulate pipelines, and polyvinyl chloride (PVC) with 1″ diameter to simulate the district networks. Through the use of many parallel gate and globe valves was chosen a properly system characteristic to simulate an individual leak in a branched type network (without loops). Figure 8 shows the network layout, highlighting:

- Path for the leakage experiment
- Pipe diameters and length

- Leak and sensor positions
- Closed valves positions
- System input and output
- Hydraulic pump system used in the experiments

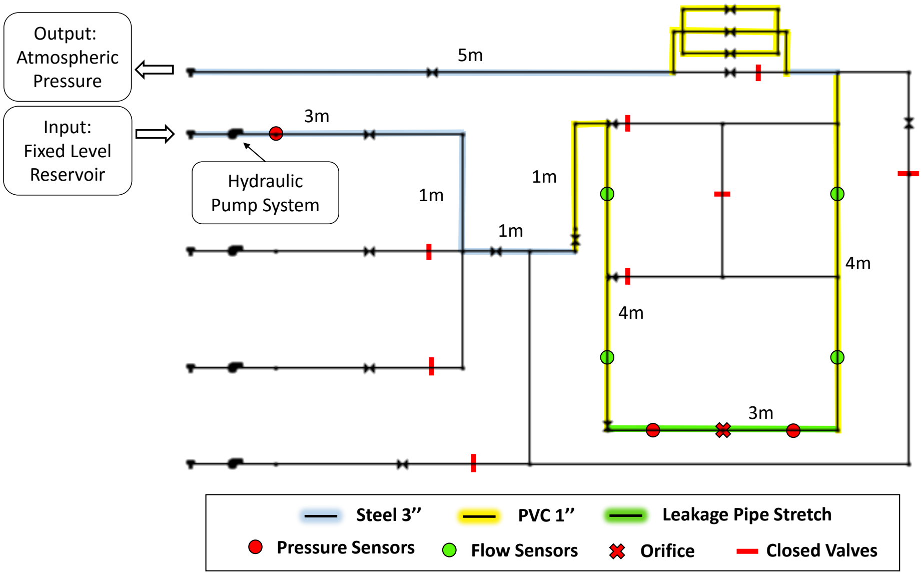

Figure 8 – Scheme of chosen network for leakage experiments.

For the experiments, the network was fed by two hydraulic pumps, reaching up to $5.0\,m^3/h$ of flow and pressure heads up to $70\,m$. Hence, it was possible to meet pressure head conditions of real WDS, since the pressure head have been shown by literature as one of the most influent parameter of leakage. Additionally, the laboratory monitoring system is composed of flow and pressure sensors placed along the network, and extra sensors have been added for the specific study, in the leak neighborhood.

The leakage experiments were performed adopting steady flow conditions in the LENHS network, by setting a constant rotation of the hydraulic pump system which meets the required pressure upstream the leakage. The modulation of the hydraulic pump system was made by the use of frequency inverters, which allows decreasing the pumps frequency from the usual value of $60\,Hz$ down to $30a, Hz$. This method actually decrease the input of hydraulic energy in the network, and is suitable for adjust the system pressure in an interest point. Thus, for each individual test the pumps rotation was set to establish different pressure heads in the leak point, and after an accommodation period for the system establish a steady flow condition, the measurement of the leakage flow was performed.

In order to guarantee a better control over the leakage phenomenon and data quality in experiments tests, a *submerged leakage structure* was built to keep it under a constant external pressure $h_{ext} \approx 80\,cm$ (Figure 9). This enhancement in comparison to

Table 3 – Sensors characteristics

Sensor	Brand	Model	Physic Principle	Accuracy	Full Scale
Pressure Head	GE Druck	PTX 7217	Piezoresistive	$\pm 10\,cm$ $\pm 0.1\,\%$ FS	$100\,m$
Flow	Krohne	Optiflux 1000 IFC 010	Eletromagnetic	$\pm 0.016\,m^3/h$ * $\pm 0.3\,\%$ FS	$5.3\,m^3/h$

*The accuracy decreases for low flow condition.

previous leakage experiments was developed due to several preliminary tests, which have pointed to great instability of the leakage phenomenon when discharge to atmosphere. The main hypothesis that justify such instability is that the leakage jet high velocity induce instable motion of the air in leak neighborhood, which leads the external pressure variations. It was observed that the proximity of small pieces to collect the leakage flow also interfere the phenomenon. Therefore, by submerging the orifice, the higher viscosity of the water in comparison to air have guaranteed a more stable external pressure head, and also allowed a faster and smoothly dissipation of the high kinetic energy of the leakage jet.

Indeed, perform the leakage phenomenon in a submerged pipe can improve the experiment resemblance to real cases, because when leakage from buried pipes arise in surface a constant external pressure head is establish over the leak. However, for a buried pipe, the external pressure conditions could depend of a great number of surrounding soil variables, such as: composition, compactness, humidity and Darcy's coefficient; which can affect the leakage behavior. Furthermore, although this is not subject of this research, high velocities of the leakage jet (up to $25\,m/s$ found in preliminary tests) can easily erode soil in leak neighborhood, resulting in a leakage discharge from the pipe to a water surrounding.

The constant external pressure head value adopted in the experiments was suitably chosen in a range of commons depth of pipes for WSS. Due to practical issues, the experiments were just performed under $80\,cm$ of external pressure head, and the leakage flow was not analyzed in the case of external pressure variations.

For acquiring data from the system during leakage experiments five pressure and four flow sensors were used (Figure 8), with measurements frequencies up to $1.0\,Hz$. The sensors main characteristics are presented in Table 3. In addition, an electric analyzer was also used to measure the electric energy used by both hydraulic pumps. The pressure sensors were assembled in pipes using an acrylic piece, where a round role with diameter of $1.0\,mm$ connect the pipe interior to the sensor diaphragm (Figure 10). Thus, the pressure measurements were taken in the pipe wall at same height of the cross section center line. In addition, it was opted for a redundancy measurement of pressure in leakage neighborhood, a pair of sensors upstream and downstream cross-section.

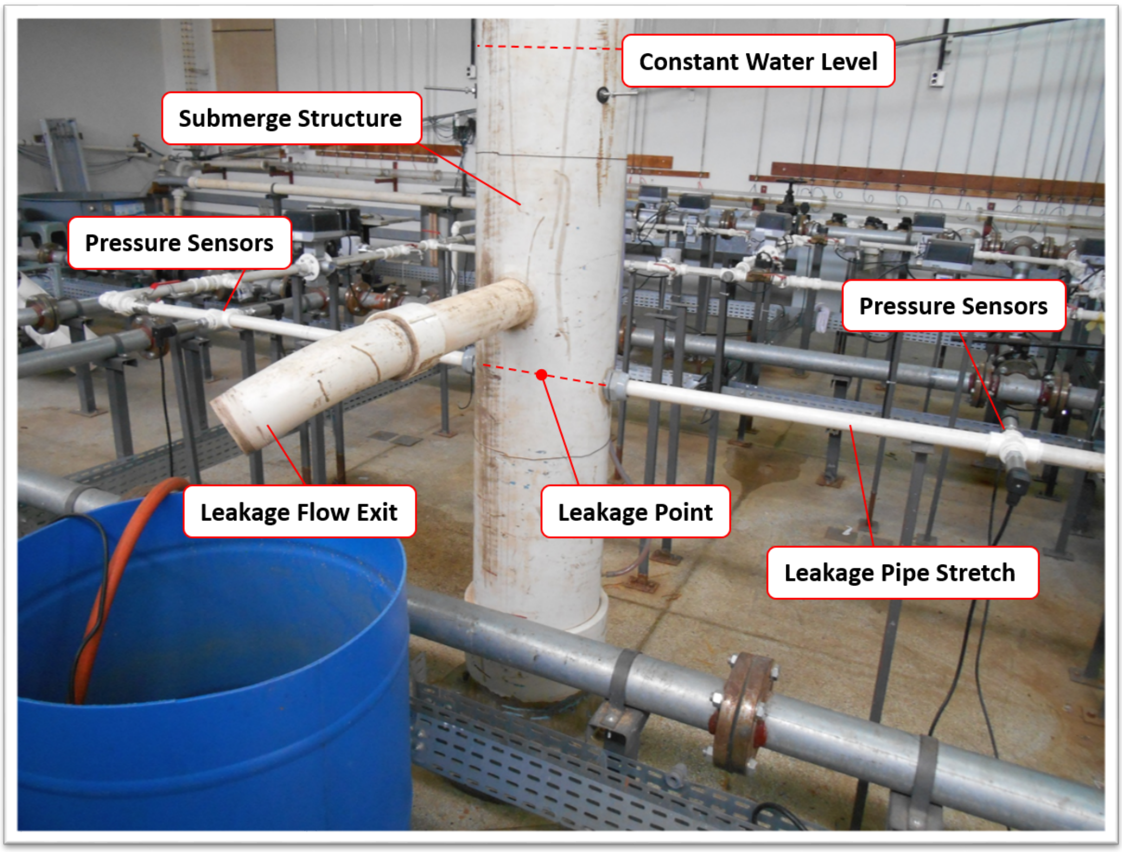

Figure 9 – Submerging structure built for the leakage experiments.

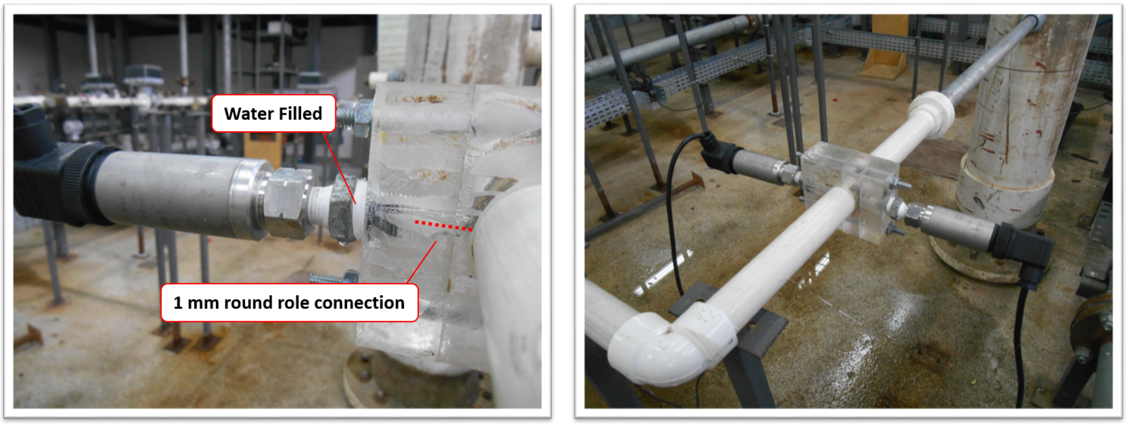

Figure 10 – Pressure sensors location

3.2.2 The Leakage Experimental Setup

The leakage experiments were performed by drilling the pipes with orifice diameters of 1.50, 2.50, 5.00 and 10.00 mm. Each orifice was tested individually, wherein the leak was placed in the middle of the selected pipe stretch (Figure 8), pointed to the ground, inside the submerged structure (Figure 11).

The experiments consider different pipe materials: galvanized steel and PVC; and two pipe diameters: $25,4$ and $7,62\,mm$ (denoted by 1" and 3"); resulting in a combination of four different conditions for the pipe stretch. All pipe stretches have the same wall

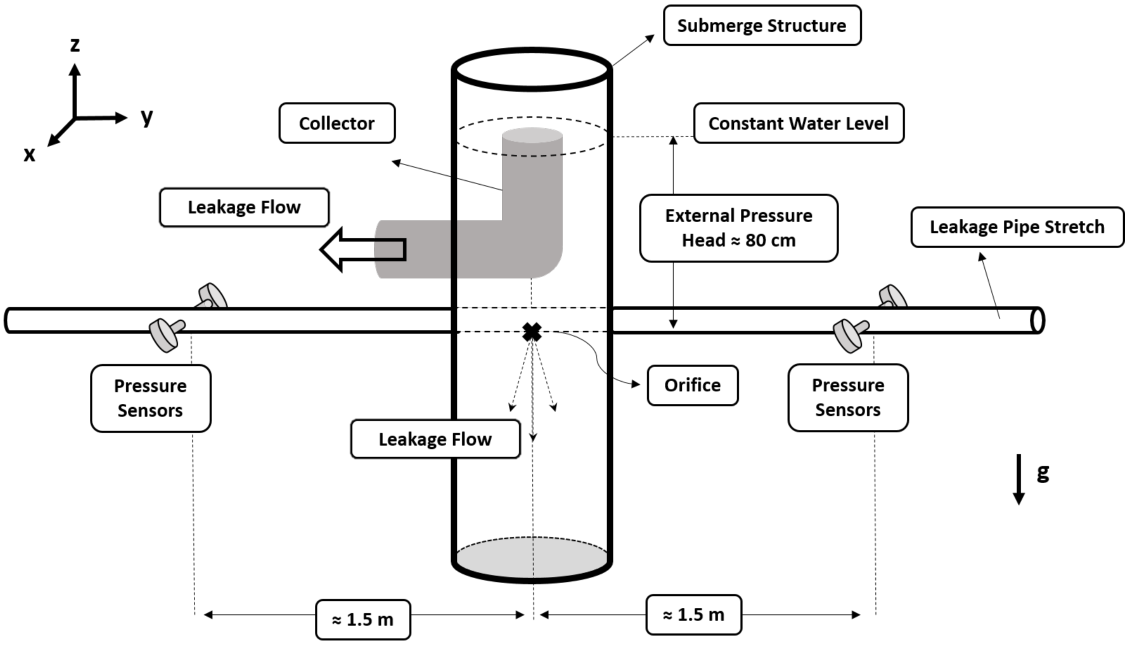

Figure 11 – Experimental scheme of the leakage experiments.

thickness $W_{pipe} \approx 4\,mm$.

The four pipe stretches and the four orifices diameters results in sixteen test groups. The pipe stretch selected for the drills was switched during the experiments, while the rest of the network remained unchanged. For each test group, thirty tests were performed under 10 pressure head levels (three tests per level) ranging from 5 to 50 m. A summary of the experiments composition is presented in Table 4.

The leakage experiments were performed by setting fixed operation points for the hydraulic pumps, which were obtained through driving pumps by frequency inverters controlled by the PLC. Thus, it was possible to setup the system in steady flow condition for specific pressure levels, to assure leakage flow measurement with accuracy. These measurements were performed by weighing stocked volumes from the leakage flow over a timed period. This method was chosen because of precision in the case of steady flows.

Special attention was given to the leakage flow exit, considering that the improper collection of the water into the measurement recipient could have influence over the leakage phenomenon. For minimizing potential interference, the submerging structure, in Figure 11, worked as a secondary reservoir between the leakage and the measurement recipient. Thus, a constant height collection of the water flow inside of the structure (Figure 12) provided the constant external pressure on the leak.

The experimental procedure consisted of weighing the measurement recipient before and after each test, over time. For this, a measurement recipient with capacity up to 150 liters, a scale with precision of 0.1 kilogram and a timer with milliseconds resolution were adopted. The indirect calculation of the leakage flow rate, was obtained by the use of

Table 4 – Experimental test composition

Pipe Material	**Pipe Diameter**	**Orifice (mm)**	**Group Test**	*** Pressure Head (m)**	**# Tests**	**# Total**
PVC	1"	1.5	1	5 – 10	30	480
		2.5	2	5 – 10	30	
		5.0	3	5 – 10	30	
		10.0	4	5 – 10	30	
	3"	1.5	5	5 – 10	30	
		2.5	6	5 – 10	30	
		5.0	7	5 – 10	30	
		10.0	8	5 – 10	30	
Steel	1"	1.5	1	5 – 10	30	
		2.5	2	5 – 10	30	
		5.0	3	5 – 10	30	
		10.0	4	5 – 10	30	
	3"	1.5	5	5 – 10	30	
		2.5	6	5 – 10	30	
		5.0	7	5 – 10	30	
		10.0	8	5 – 10	30	

* Pressure head upstream the leak point – h_{up}

Figure 12 – Water collector inside the submerging structure providing a constant external pressure on the leak.

Equation 3.1, where M_i and M_f are the initial and final weighs of the stocking recipient, and T_c is the collection period.

$$Q_{leak} = \frac{1}{\rho}\frac{M_f - M_i}{T_c} \tag{3.1}$$

The uncertainty in the average leakage flow rate δQ_{leak} was calculated by the uncertainties in the weighing and timing measurements ($\delta M = 0,1kg$ and $\delta T_c = 1s$), through the Equation 3.2. Hence, the worst precision in flow rate measurements have happened for tests with bigger leakage flows (orifice diameters of $10,00\,mm$), wherein the stocking recipient was filled in about one minute.

$$\delta Q_{leak} = \pm \frac{(M_f \pm \delta M_f) - (M_i \mp \delta M_i)}{(T_c \mp \delta T_c)} \tag{3.2}$$

The experimental proceedings are summarized by the following steps:

- Measurement of the initial weigh of the stocking recipient (M_i).
- Adjustment of the system operation point on the PLC.
- System stabilization (steady flow condition).
- Beginning of the test: leakage flow starts to fill the stocking recipient simultaneously to the timer starts.
- Main period of test: wait for the filling of the stocking recipient under steady conditions.
- End of the leakage flow to the stocking recipient simultaneously to the timer stops.
- Measurement of the final weigh of the stocking recipient (M_f).
- Emptying of the stocking recipient and prepare to the next test.

* The automatic sensors informations were recorded in the laboratory control computer and collected daily at the end of tests.

The performance of leakage experiments demanded six mouths in laboratory work, and have resulted in approximately 500 data points, each one representing a single "photography" of the system under steady flow condition. In sequence, all data has been processed, which consists of a detailed analysis of each parameter acquired, for estimate the average and uncertainty values for each test, presented in the thesis annexes.

3.3 SUMMARY OF THE CHAPTER

The need of experimental studies to confirm theoretical relationships about leakage in WDS has been gaining ground, since unexpected behaviors were reported in literature. However, the few experimental approaches in the area are very heterogeneous and still insufficient. In this context, a new experimental approach was proposed, where leakage through round roles were tested in a complex pressurized system, aiming the evaluation of leaks hydraulic characteristics and their relationships with the system energy use, for several operational conditions.

The experimental approach was aimed to simulate a real WDS. Initial tests taking with the leakage flow exposed to atmosphere, which is the common practice in previous studies, have shown that the leakage phenomenon was significant affected by external conditions. This influence could be explained by induction of air fluxes due to fast water jet at the leak exit, which could have influenced the external pressure at the leak point. Therefore, the second main effort of the proposed experimental set up consisted of the build of a submerging structure, capable of establish a constant pressure head over the leak exit and infers a discharge into a surrounding water medium.

In addition, the experiments were performed for 16 test groups, for different orifice diameters, pipe materials and pipe diameters, what make possible the evaluation of leakage behavior for many operational conditions.

4 LEAKAGE ANALYSIS FROM A HYDRAULIC PERSPECTIVE

"From the above analysis of the state-of-the-art, it seems that the definition of a leak law for a single leak in a pipe is not trivial. But even if a reliable law is derived for this case, still an open question remains: is it possible to use a leak law for a whole network or district?"

Ferrante, Meniconi e Brunone (2014)

The hydraulic behavior of leakage through round holes is commonly described by the *orifice equation* (Equation 2.11, p. 41), which is typically valid when leakage flows are turbulent ($Re_{leak} > 10^5$). However, the effectiveness of such relation for lower Reynolds numbers and under different pipe conditions (diameter and material) is not fully explored.

In this context, the performance of leakage experiments proposed in previous chapter have allowed a better assessment of the leak phenomenon through round roles in a complex pressurized system.

In this research, the leakage experiments have shown different results when compared with literature. This chapter presents an analysis of the leakage experiments from a hydraulic perspective, investigating the main causes of distinct leakage behaviors.

4.1 DYNAMICS OF THE SYSTEM

During the leakage experiments high flow dynamic were observed, being mainly observed by large oscillations in pressure head data (sampling rate = 1 Hz), which preserved a constant average, but instantaneously measurements have fluctuated in significant ranges (Figure 13). This phenomenon is consequence of intrinsic system dynamics, due to effects of flow compressibility and common oscillations on the hydraulic pumping system. Moreover, in the case of real WSS, the continue changing in demands causes a constant superposition of small transient flows, thus similar dynamics of the pressure head are expected (MAYS, 2000).

In order to model the leaks with steady flow assumption, it was adopted the average pressure head for both sensors upstream and downstream the leak point and for each test. Figure 14 presents the evolution of pressure head average for a typical test, highlighting its difference to final average evolution, which become lower then $2\,cm$ after approximately $3\,min$ of data acquisition ($\approx$ 200 data points). Furthermore, the series standard deviation was adopted as the average pressure head uncertainty. In order to ensure the quality of pressure head measurements, tests with higher uncertainty was discarded.

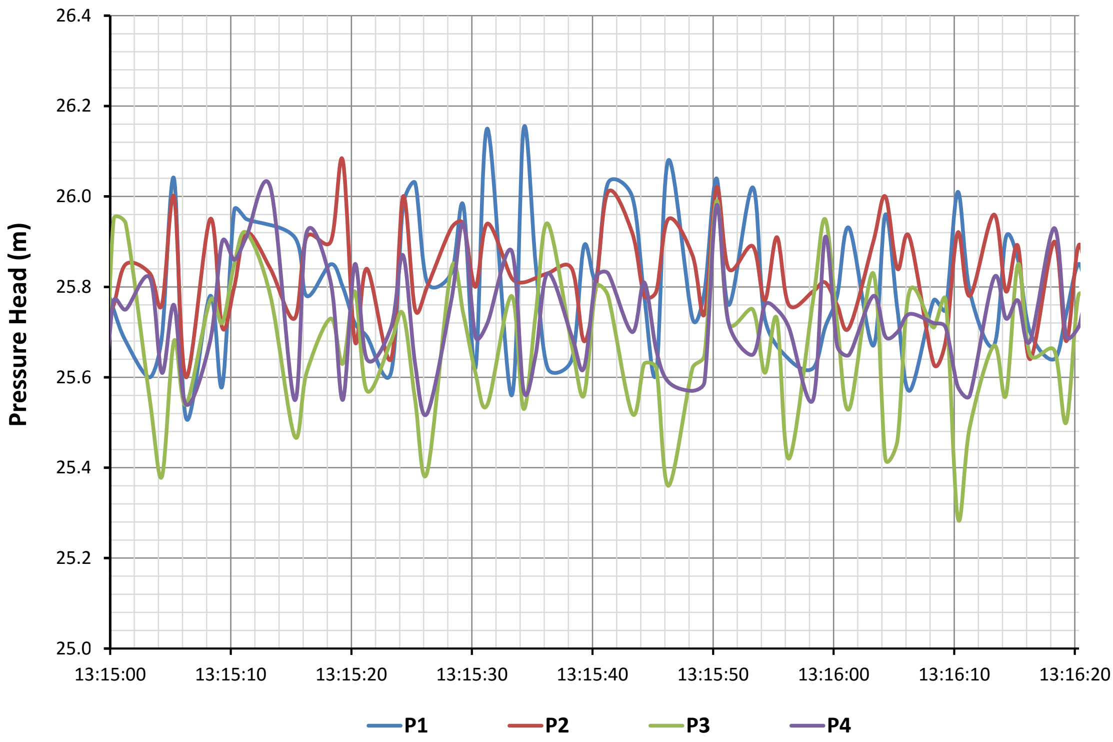

Figure 13 – Typical pressure head measurements oscilations during leakage experiments

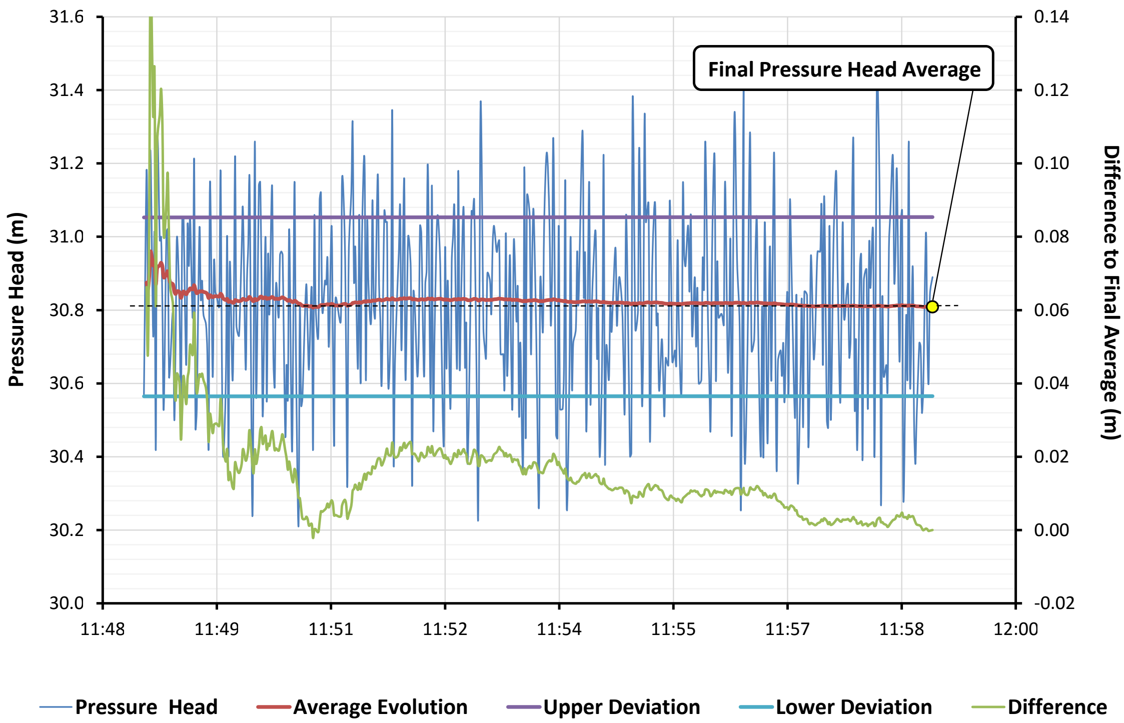

Figure 14 – Pressure head average evolution and standard deviation for a single test

Although the further leakage analysis were performed considering just the average pressure head of the system, it is important to observe that leakage hydraulic characteristics can be direct affected by system dynamics.

4.2 LEAKAGE FLOWS AND SYSTEM PRESSURE HEAD

The experimental results regarding the relationship between leakage flows and system pressure head, for distinct pipe stretches and orifice diameters, are presented in Figures 15, 16, 17 and 18.

Since the experiments were performed with a constant external pressure head over the orifice ($h_{ext} \approx 80\,cm$), their hydraulic behavior is governed by the *pressure head drop* in the orifice, which is the difference between the pipe pressure head upstream leakage and external pressure head (Equation 4.1). Further analysis on leakage flow is based in the pressure head drop in the orifice ($\Delta h_{orifice}$) instead of pipe pressure head upstream leakage.

$$\Delta h_{orifice} = h_{up} - h_{ext} \tag{4.1}$$

In the charts, additionally to experimental data, are highlighted the theoretical behavior of the leakage flow, described by the *orifice equation* (Equation 2.11, p. 41), adopting $C_d = 0.6$ (common value used in literature for turbulent flow – Section 2.2.1). The results were presented in groups gather by orifice diameter to allow a better view of the differences between each one of four pipe stretches, because flow rates are directly proportional to orifice areas and prevents a properly display with a fixed flow scale.

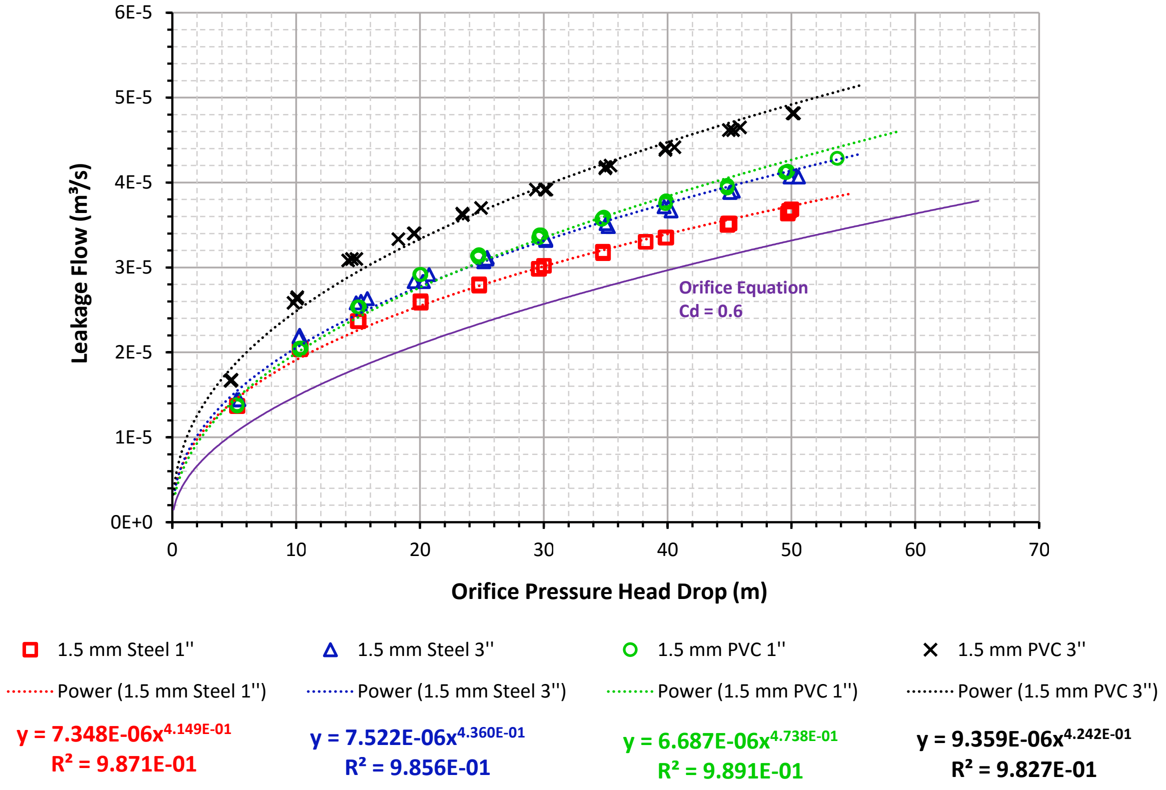

Figure 15 – Leakage flow rate vs. pressure head for orifice diameters 1.5mm

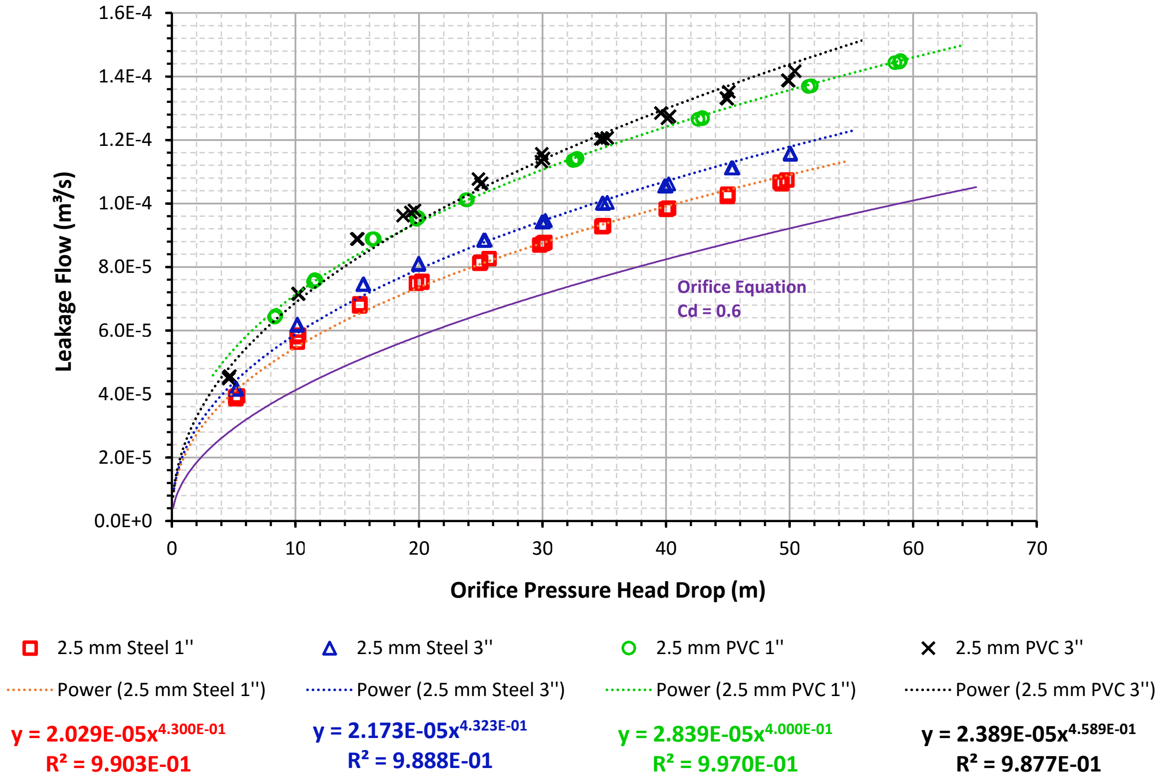

Figure 16 – Leakage flow rate vs. pressure head for orifice diameters 2.5mm

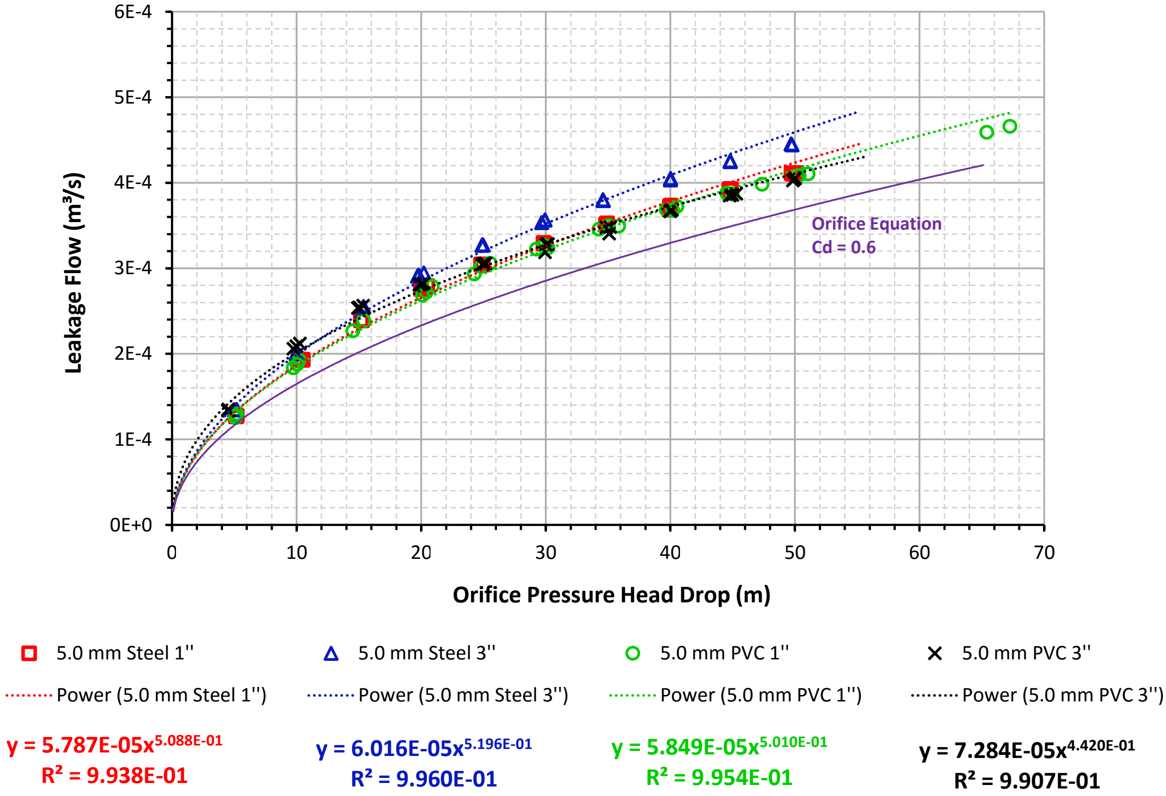

Figure 17 – Leakage flow rate vs. pressure head for orifice diameters $5.0mm$

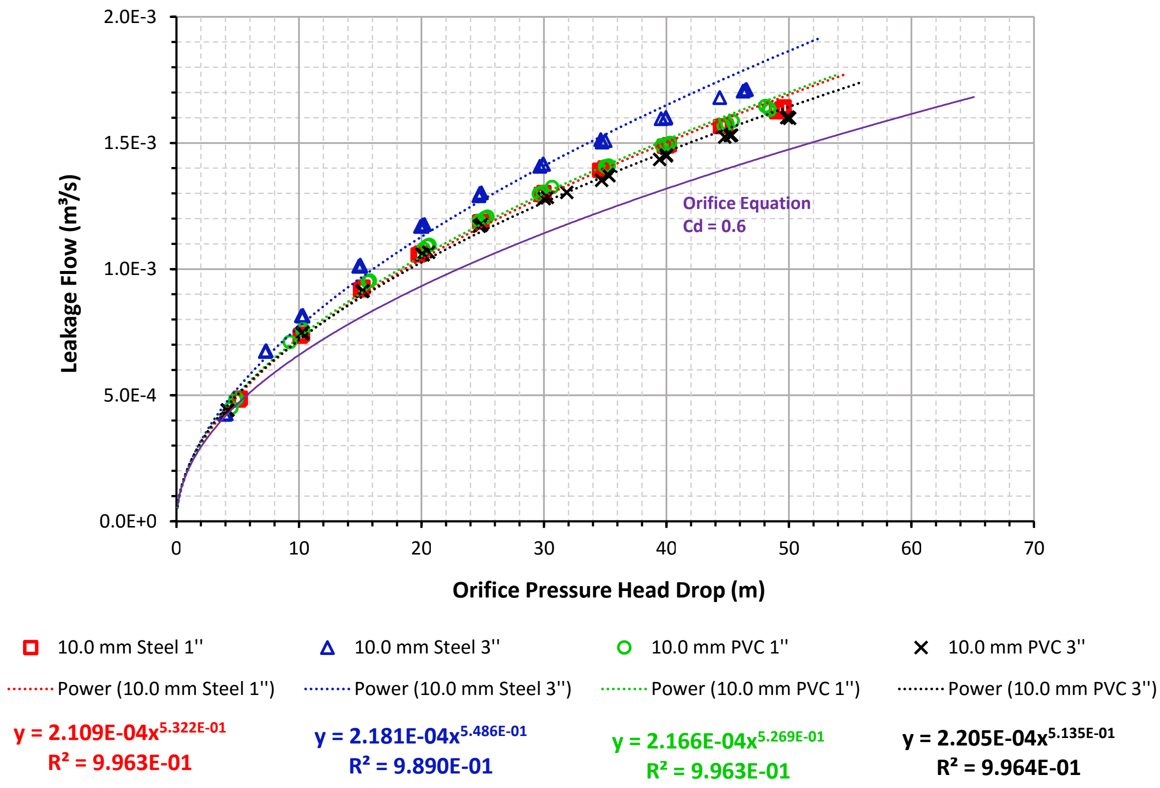

Figure 18 – Leakage flow rate vs. pressure head for orifice diameters 10.0mm

These results demonstrate that different materials and pipe diameters caused greater impacts at smaller leaks (1.50 and 2.50 mm). In both cases, larger pipe diameters and PVC pipes have shown greater leakage flow rates, what complies to the FAVAD concept of pipes elasticity, since PVC have higher elasticity then steel pipes (ZYL; CASSA, 2014). However, in the case of larger orifices diameters (5, 00 and 10, 00 mm) the same logic fails, and just the results for the galvanized steel pipe with 3" diameter are highlighted, being significant higher then others groups. Is noteworthy that this analysis are intrinsic to flows scales and have aimed to highlight the contrasts of the distinct four pipe stretches, which showed to affect leakage flows for identical orifice sizes.

The *orifice equation* using $C_d = 0.6$ tend to underestimate the leakage flows for all tests. However, the power functions adjusted for the tested groups show that the best exponents to fit a similar curve to experimental points differs from $N1 = 0.5$ (predicted by the orifice equation) in many cases.

To assess the group tests main differences, the leakage flow and the orifice pressure head drop were normalized, according to the respective maximum values of each group, presented in the chart of Figure 19. The chart demonstrates that the relationship between the leakage flow and system pressure head are very closely between the test groups, presenting grater differences for lower pressures. Although the fitted function has a good correlation coefficient, the differences of the maximum leakage flow and pressure head for each group (used to normalize the data points), difficult the practical application of this equation.

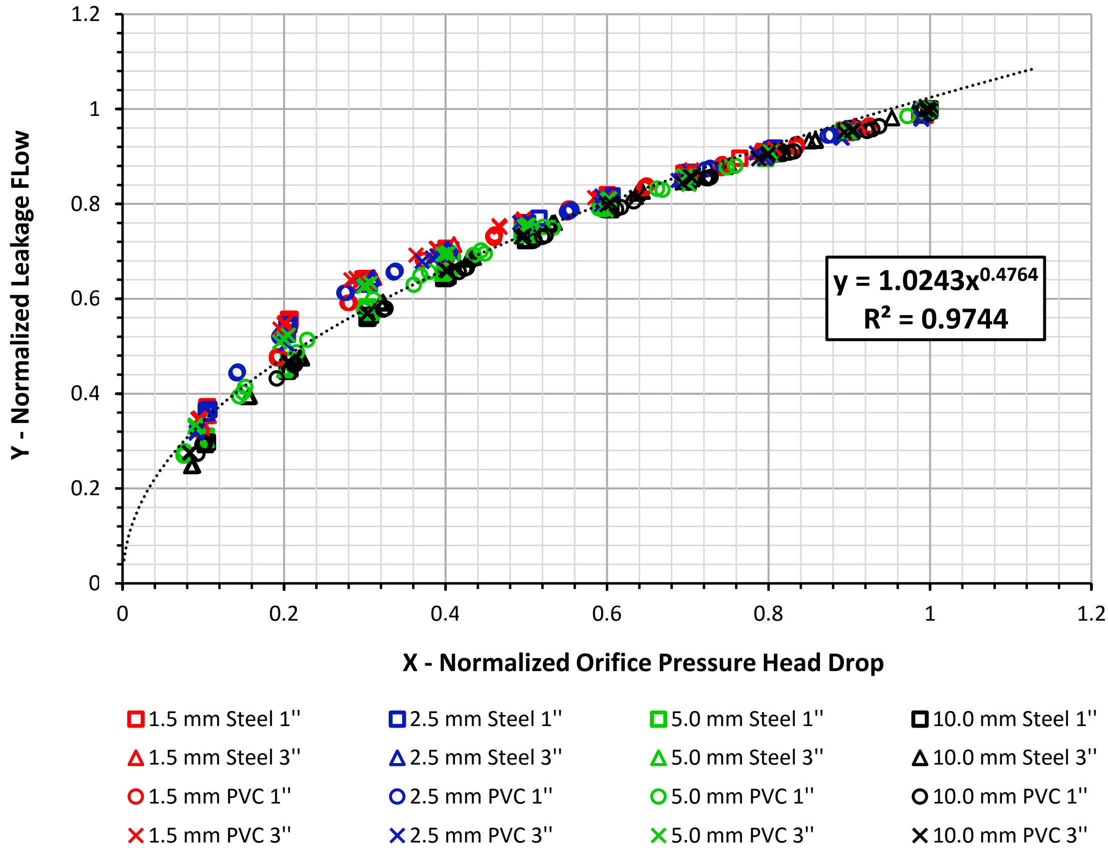

Figure 19 – Normalized leakage flow vs normalized pressure head drop

In order to better assess the physical behavior of the leakage, it was also proposed the evaluation of *leakage flow average velocity* V_{leak}, by Equation 4.2. Thus, all results could be presented in the same scale, offering a better understanding of the sixteen different test groups (Figure 20). In this case, effects of flow contraction are being neglected, since estimations of the contraction coefficient demand further efforts and are not in the scope of this work. Hence, the real average speed is supposed to be higher than estimations of Equation 4.2, since the cross section area at vena contracta is smaller than the orifice area.

$$V_{leak} = \frac{4\, Q_{leak}}{\pi\, D^2_{orifice}} \tag{4.2}$$

The leakage average velocities in Figure 20, have shown lowers dispersions for the steel pipes than the PVC ones, but still presented differences between curves. Additionally, it highlights high speeds of the leakage jet, up to $25\, m/s$, which can easily erode many kinds of soils and produce real conditions similar to the experiment setup adopted. These velocities magnitudes were not found in previous reports, and most of the research did not addressed concerns about external soil influences. Furthermore, results for PVC pipes with orifice diameters of 1.5 mm and 2.5 mm presented higher leakage average velocities than the majority, but this result could be masked by eventual increase of orifice areas due to pipes elasticity, which could lead to greater areas and lower velocities.

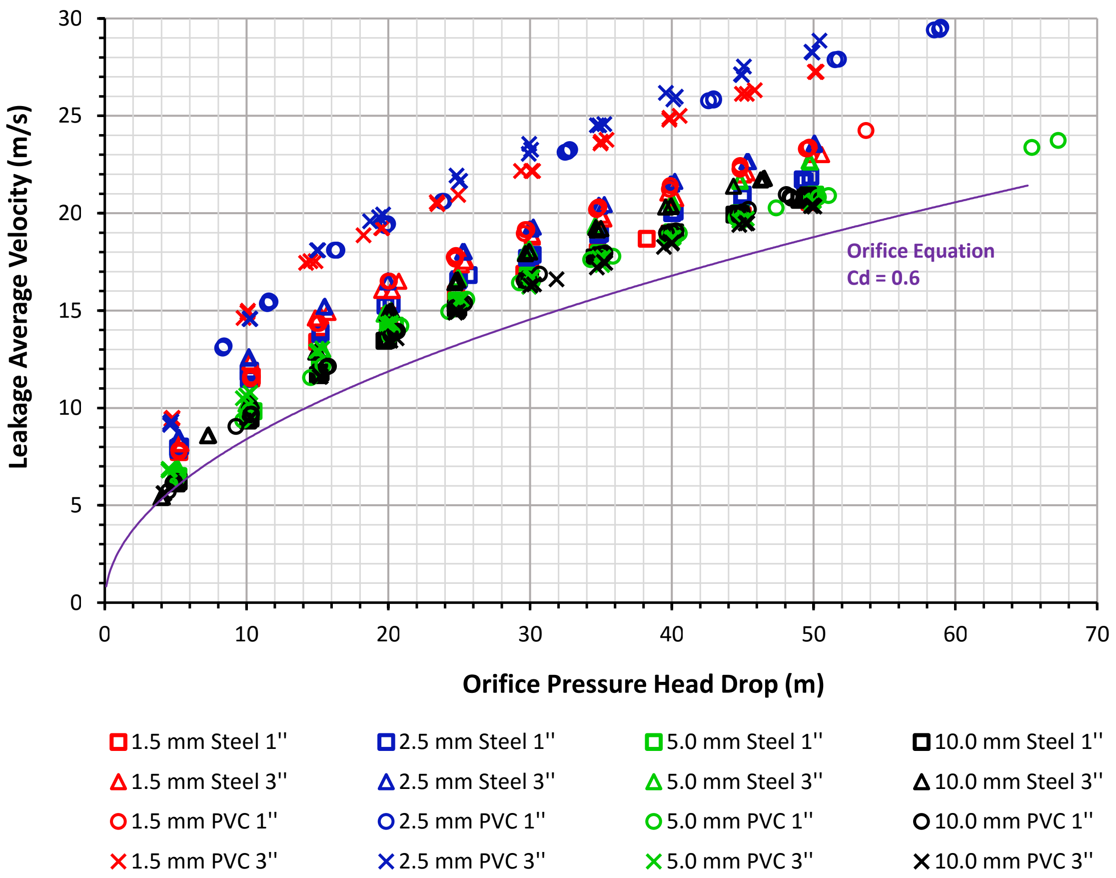

Figure 20 – Leakage average velocity vs. pressure difference for all tests

Next, a more detailed analysis regarding leakage flow estimations errors is presented, focusing in the use of the orifice and power equations. Although the adjusted power functions appears to precisely fit the experimental data in previous figures, further investigation have shown the occurrence of considerable errors.

4.3 ERRORS IN LEAKAGE FLOW ESTIMATIONS

Assuming that leakage in WDS is a complex phenomenon and can occur under several different conditions, it becomes necessary to assess the effectiveness of leakage flow estimations by simplified equations. Furthermore, the practical use of these equations commonly employ constant coefficients, what can increase errors. Therefore, based on experimental data acquired in leakage experiments, this section propose a detailed investigation of the orifice and power equations (Equations 2.11 and 2.15), which are the most used relations to estimates leakage flows in WDS.

To analyze the *orifice equation* effectiveness, a discharge coefficient C_d was estimated for each experimental data point, by isolating the variable in Equation 2.11, which results in 16 C_d series according to 16 test groups (Figure 21). The discharge coefficients appears to behave like expected by theory (Chapter 2 Figure 5), but in different levels for each group tested. It is important to note that all C_d values estimated for the round orifices in the leakage experiments were greater then the commonly used value of $C_d = 0.6$, adopted for turbulent flow. Furthermore, some values granter then 1.0 occur for PVC pipes, which are inconsistent to the *orifice equation*, what may suggest that this approach is inappropriate to predict leakage flows in this situations.

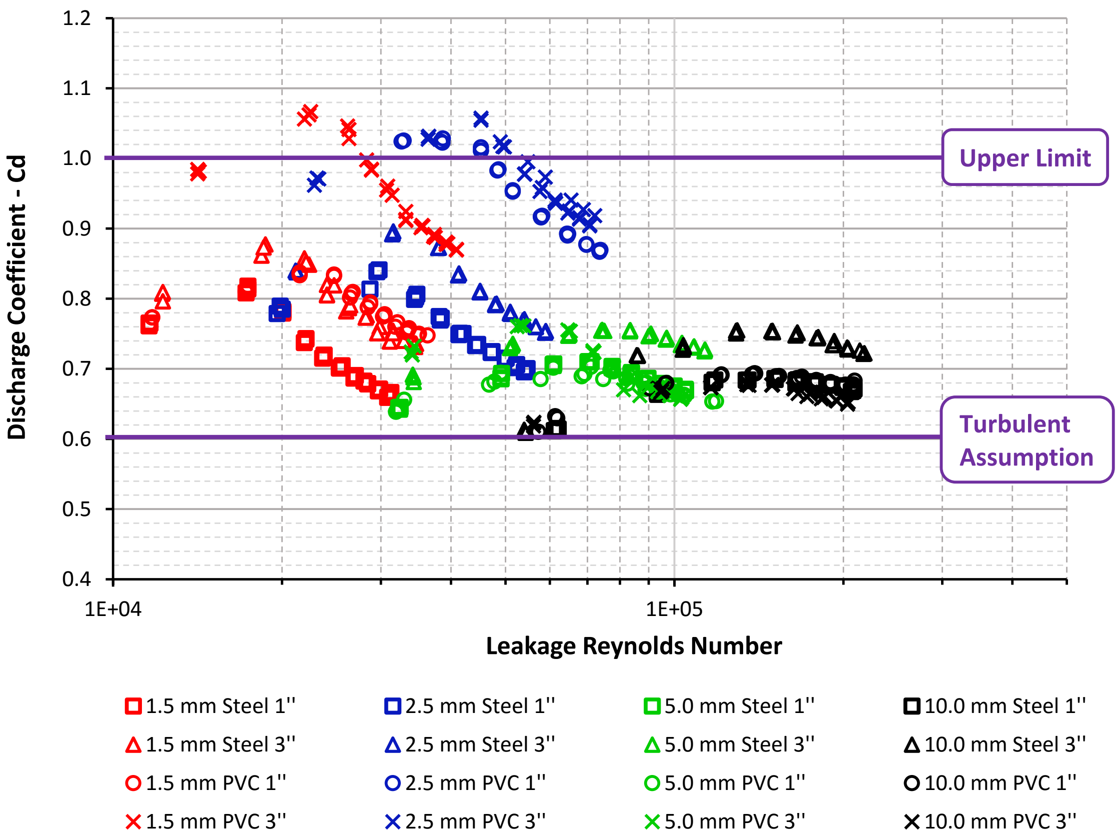

Figure 21 – Discharge coefficients series for leakage experiments

In order to establish the best discharge coefficients to represent each test group, the average of discharge coefficients series were calculated (Table 5). Attention was brought to some high C_d values for smaller orifices, which have a theoretical upper limit of 1.0. Such results may suggest that the *orifice equation* is inadequate to predict leakage behavior in this conditions, since experimental data were carefully acquired and repeatedly accuse C_d values physically incoherent.

Although such values relate the best coefficient adjustment to employ on the *orifice equation*, the use of constant values for C_d produce errors in the estimation of leakage flow. The differences between measured and estimated leakage flow is calculated

Table 5 – Discharge coefficients adjusted by experimental data

Orifice (mm)	C_d			
	Steel 1"	**Steel 3"**	**PVC 1"**	**PVC 3"**
1.5	0.72	0.79	0.79	0.95
2.5	0.75	0.81	0.95	0.97
5.0	0.69	0.74	0.68	0.70
10.0	0.67	0.72	0.68	0.66

by Equation 4.3, where Q_{meas} = measured leakage, Q_{est} = estimated leakage, Q_{diff} = their difference.

$$Q_{diff} = Q_{meas} - Q_{est} \tag{4.3}$$

Thus, the percentage errors are estimated by Equation 4.4, where Q_{error} = percentage leakage error. Hence, negative errors corresponds to overestimated leakage and positive to underestimated.

$$Q_{error}(\%) = \frac{Q_{diff}}{Q_{meas}} \tag{4.4}$$

In Figure 22 are presented the errors of leakage flow estimations by the orifice equation with discharge coefficients from Table 5. The errors vary from -20% to 10%, and show explicit tendencies according to the orifice pressure head drop. For the grater orifice diameters the higher errors occurs for low pressures, while for smaller orifices underestimates prevail for pressure heads below $25\,m$ and overestimates for upper pressure values. In contrast, if the common value of $C_d = 0.6$ was adopted instead of the adjusted discharge coefficients, the errors vary from 1% to 44%, being all points underestimated (Figure 23).

In order to validate the previous error analysis, a comparison between the *absolute difference between estimated and measured leakage* and the *maximum measurement uncertainty* ψ_{leak} (given by Equation 4.5, where δQ_{leak} is the leakage flow uncertainty from Equation 3.2) is also proposed in Figure 24.

$$\psi_{leak} = 2\,\delta Q_{leak} \tag{4.5}$$

In the chart, all points above the highlighted line represent tests where absolute differences between measured and estimated leakage are greater than the measurements uncertainty. As the majority of tests is above the line, those differences in leakage flow estimations with the orifice equations (using optimized C_d values) can not be justified by the experimental method adopted (in exception of the case of $10.0\,mm$ orifice diameter).

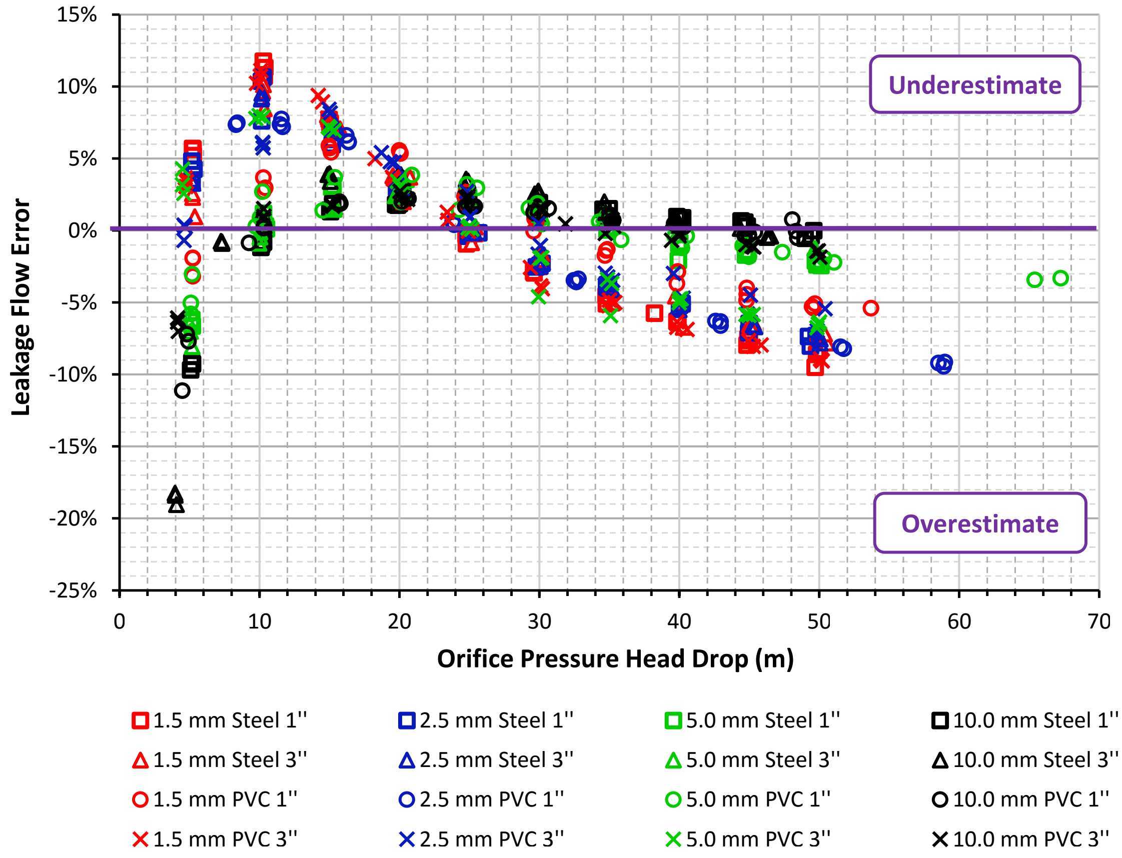

Figure 22 – Errors in leakage flow estimations with the orifice equation

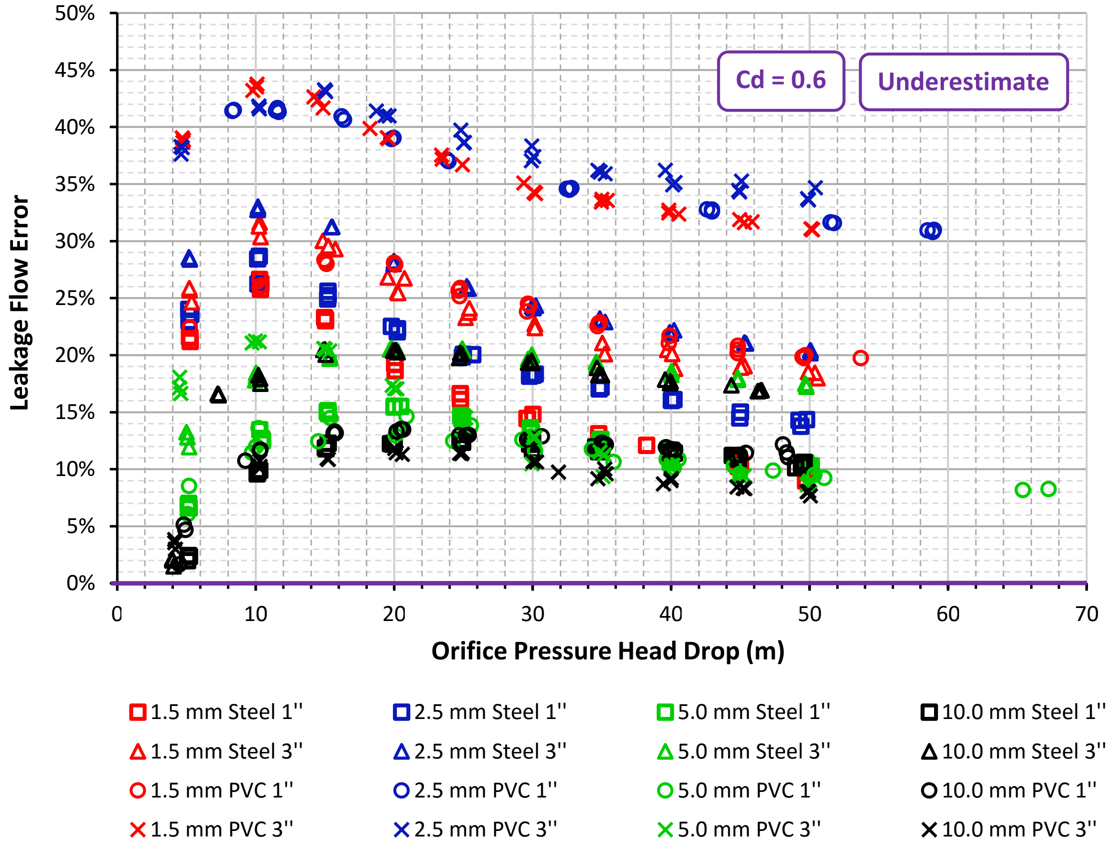

Figure 23 – Errors in leakage flow estimations with the orifice equation considering $C_d = 0.6$

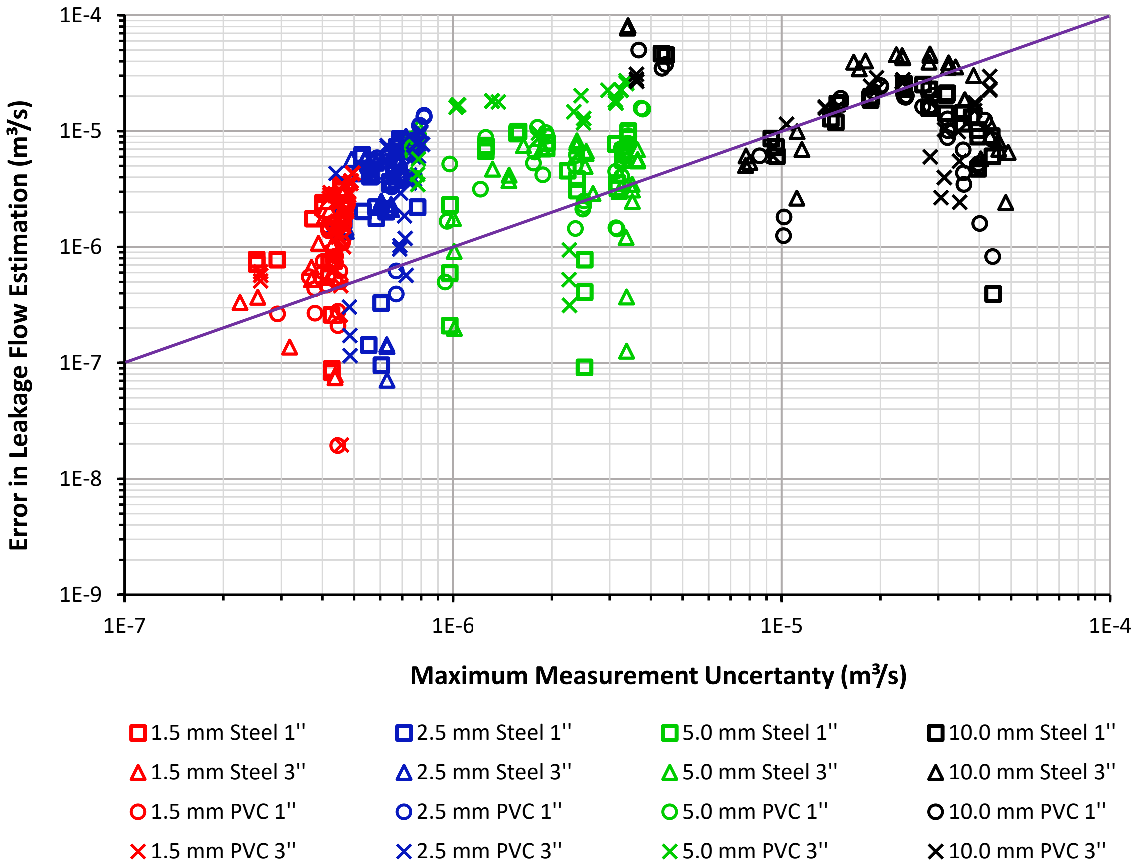

Figure 24 – Difference between measured and estimated leakage flows by orifice equation in function of the measurements maximum uncertainty

In contrast to the *orifice equation*, effectiveness in leakage estimations by the *complete power equation* (Equation 2.15) depends on the adjustment of two coefficients: C_L and $N1$. Hence, *power functions* were fitted to the collected data by the last square method (Figures 15, 16, 17 and 18), and sixteen pairs of coefficients (C_L and $N1$) were calculated from the fitted curves coefficients (Table 6).

Table 6 – Adjust coefficients for the *complete power equation* estimated from experimental data

Orifice (mm)	C_L | $N1$			
	Steel 1"	**Steel 3"**	**PVC 1"**	**PVC 3"**
1.5	0.94 | 0.41	0.96 | 0.44	0.86 | 0.47	1.20 | 0.42
2.5	0.93 | 0.43	1.00 | 0.43	1.31 | 0.40	1.10 | 0.46
5.0	0.67 | 0.51	0.69 | 0.52	0.67 | 0.50	0.84 | 0.44
10.0	0.61 | 0.53	0.63 | 0.55	0.62 | 0.53	0.63 | 0.51

The errors in leakage flow estimations by the *complete power equation* using the adjusted coefficients were also calculated employing the Equation 4.4, the results are shown in Figure 25.

The errors presented in Firgure 25 are similar to the orifice equation with adjusted coefficients (Figure 22), but different patterns that have been observed between smaller and larger orifices for the *orifice equation errors* no longer exist. This evidence points to the need of the exponent coefficient variation for establish a consistent relationship between leakage flows and system pressures, $N1$ have shown to increase according the orifice size (Table 6), which is the main difference between both equations. Moreover, the errors are lower for the power relationship, most of data points are restrained in the range from -5% to 5%, and as before, the greatest errors occurs for low pressures.

The same validation performed for the orifice equation estimations regarding the leakage flow measurements uncertainty (Equation 4.5) is also proposed for the complete power equation estimations, presented in Figure 26. As before, the chart shows that the majority of leakage flow estimations errors by the power equation (using optimized coefficients C_L and $N1$) can not be justified by the experimental method adopted, since they are above the highlighted line.

The present error analysis concludes that the orifice and the complete power equations can be used to represent leakage through round orifices in the experimental conditions proposed. However, both equations are based in leakage phenomenon simplifications, and associated errors must be accounted for. Stands out that such errors can increase significantly by employing not optimal coefficients C_d, $N1$ and C_L, which shown to considerably vary between the 16 different test groups A more detailed analysis regarding the equation coefficients is presented in sequence, aiming to link their behavior to flow hydraulic characteristics.

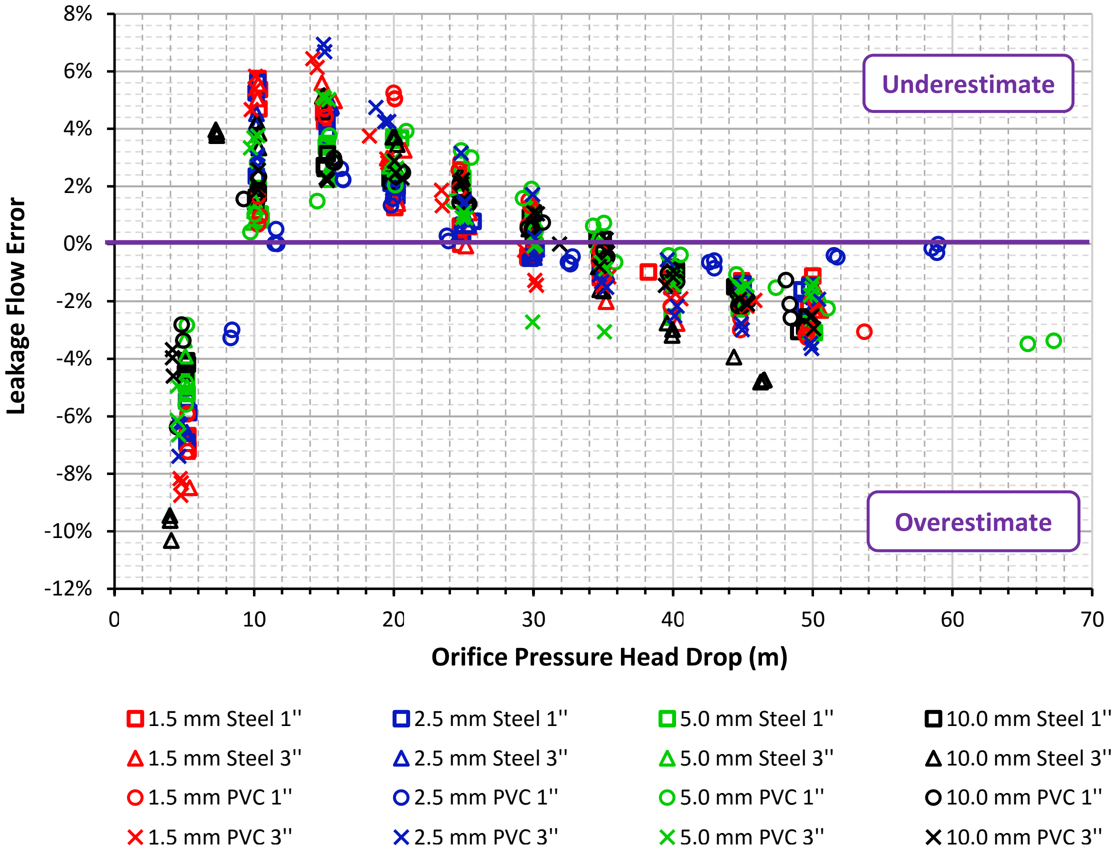

Figure 25 – Leakage flow errors for complete power equation estimations (Equation 2.15)

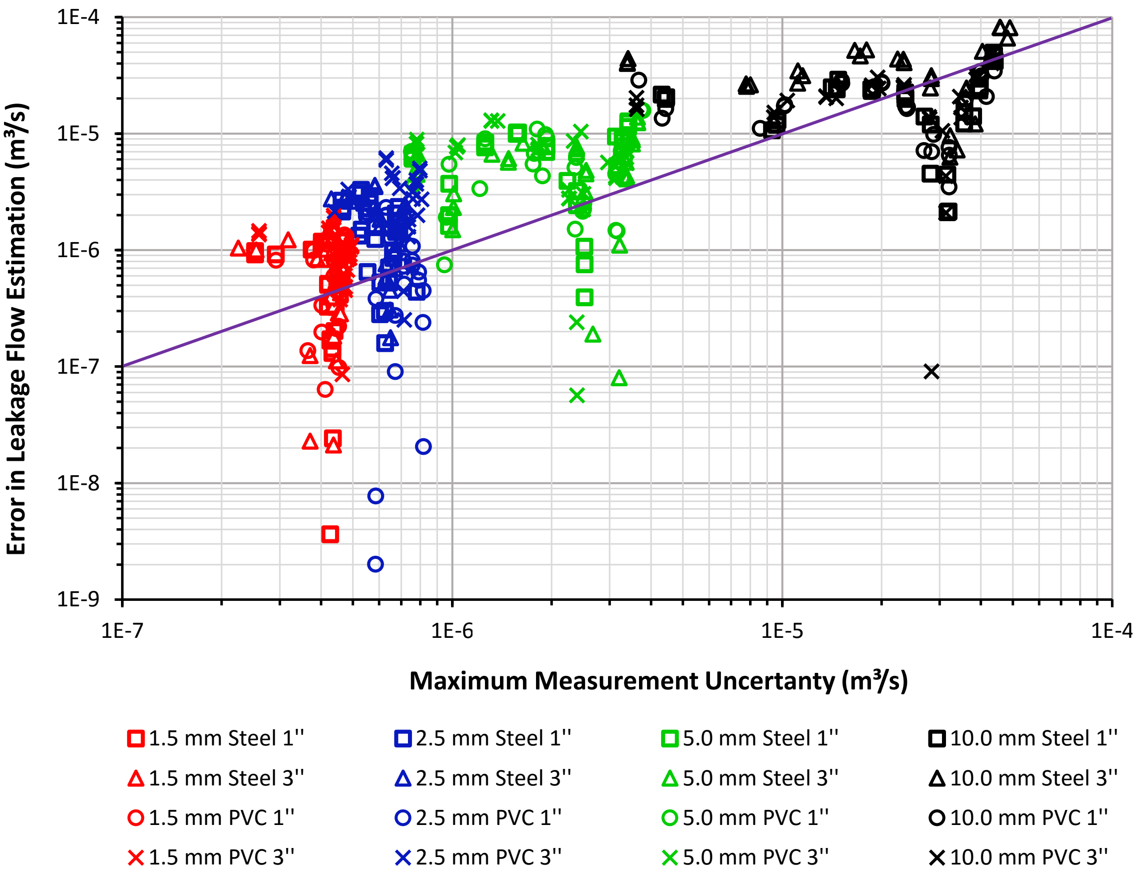

Figure 26 – Difference between measured and estimated leakage flows by power equation in function of the measurements maximum uncertainty

4.3.1 Coefficients Analysis

Complementary, a statistical analysis of coefficients C_d, $N1$ and C_L was performed to evaluate its standard deviation σ and maximum dispersion ψ for the 16 group tests. The analysis of these coefficients allow a better comprehension about the physical characteristics of the leakage phenomenon, since most of its complexity is suppressed in this parameters. The Reynolds number for the leakage flow – Re_{leak} was chosen to demonstrates the coefficients relationships according to leakage flow regimes.

The statistical analysis of the discharge coefficients was performed according to C_d series of Figure 21, resulting in Table 7.

Table 7 – Statistical analysis of discharge coefficient – $\boldsymbol{C_d}$

Orifice (mm)	$\boldsymbol{C_d}^*$ | $\boldsymbol{\sigma}$(%) | $\boldsymbol{\psi}$(%)			
	Steel 1"	**Steel 3"**	**PVC 1"**	**PVC 3"**
1.5	0.72 | 6.8 | 22.0	0.79 | 5.7 | 18.5	0.79 | 3.9 | 11.4	0.95 | 6.9 | 20.8
2.5	0.75 | 5.8 | 19.3	0.81 | 5.8 | 17.8	0.95 | 6.6 | 17.0	0.97 | 4.8 | 15.9
5.0	0.69 | 2.8 | 9.90	0.74 | 2.6 | 10.1	0.68 | 2.5 | 9.50	0.70 | 5.3 | 15.0
10.0	0.67 | 3.1 | 11.0	0.72 | 5.5 | 20.1	0.68 | 2.9 | 12.3	0.66 | 2.5 | 9.30

* Values from Table 5.

This results shows standard deviations σ of C_d up to 6.9%, and tendencies to decrease for greater orifice diameters, while the maximum dispersion ψ reach values three times greater than σ, up to 22%. Such values can be used as a basis for estimate coefficients errors in similar conditions.

Regarding to the leakage pipe stretch conditions, it was observed larger discharge coefficients for small orifices in PVC pipes, and a tendency of higher coefficients for greater pipe diameters. However, the statistical analysis appears to be consistent among different pipe stretches, with exception of the maximum dispersion for the $10,0\,mm$ orifice in the 3 inches steel pipe. Therefore, the results differences for similar conditions seems to correctly represent the individual material influence in the discharge coefficient. It is important to remember that all pipes have the same wall thickness ($W_T = 4\,mm$), and the orifices were drilled by the same method and tools.

In the case of coefficients from the complete power equation (C_L and $N1$), a complete data series for each one must be previously estimated in order to perform a statistical analysis. For evaluate an individual exponent coefficient $N1$ for each of the 480 tests, the optimal leakage coefficients from Table 6 were assumed as constants, respectively to each test group. The resulting data series for $N1$ is presented in Figure 27, as function of the leakage Reynolds number.

Figure 27 shows that the exponent coefficient $N1$ depends on the orifice diameters and also on pipes material and diameter. Also, it is behavior is an evidence of the smoothly

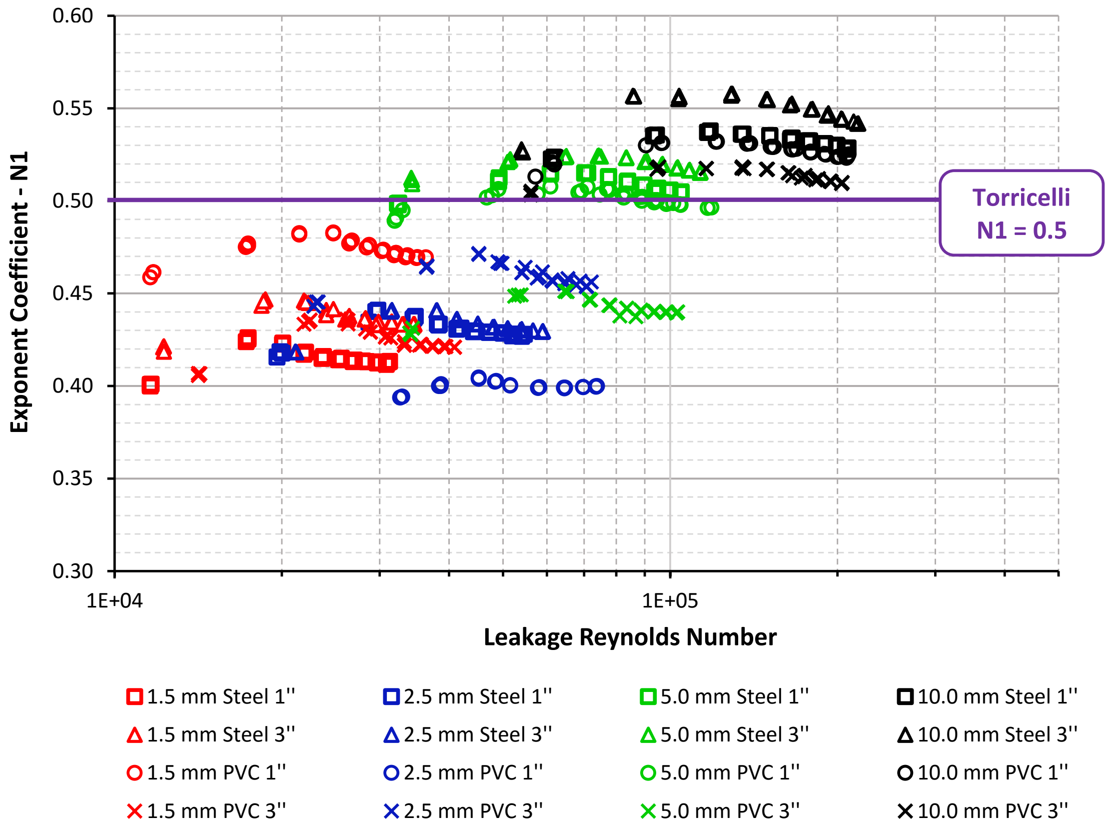

Figure 27 – Exponent Coefficient $N1$ data series for leakage experiments

coefficient tendencies according to the leakage Reynolds number. The standard deviation σ and maximum dispersion ψ for the $N1$ series were also evaluated, resulting in Table 8.

The $N1$ analysis highlights the values ranging from 0.40 to 0.55, while it was expected that $N1$ remains constant around 0.5 for round holes (WALSKI et al., 2009). It was also observed a tendency of increasing $N1$ values with larger orifices diameters. Nevertheless, the standard deviation remains around 1% for all group tests, and have not shown explicit relationship with different conditions simulated. In the case of $N1$ maximum dispersion, it reaches to 7.2% and had shown a tendency to decrease for higher values of $N1$, which have occur for larger orifices diameters.

Table 8 – Statistical analysis of coefficient $\boldsymbol{N1}$

Orifice (mm)	$\boldsymbol{N1^*}$ | $\boldsymbol{\sigma(\%)}$ | $\boldsymbol{\psi(\%)}$			
	Steel 1"	**Steel 3"**	**PVC 1"**	**PVC 3"**
1.5	0.41 | 1.5 | 6.3	0.44 | 1.6 | 6.5	0.47 | 1.3 | 5.1	0.42 | 1.9 | 7.2
2.5	0.43 | 1.3 | 5.9	0.43 | 1.4 | 5.3	0.40 | 0.6 | 2.7	0.46 | 1.5 | 6.2
5.0	0.51 | 1.0 | 3.4	0.52 | 0.8 | 3.0	0.50 | 0.9 | 3.7	0.44 | 1.4 | 5.3
10.0	0.53 | 0.8 | 2.8	0.55 | 1.6 | 5.8	0.53 | 0.8 | 3.6	0.51 | 0.8 | 2.9

* Coefficient $\boldsymbol{N1}$ values from Table 6.

Similarly to the $N1$ coefficient, the evaluation of the leakage coefficient C_L data series were performed adopting constant $N1$ values according to the 16 test groups. The data series for the leakage coefficient C_L is presented in Figure 28.

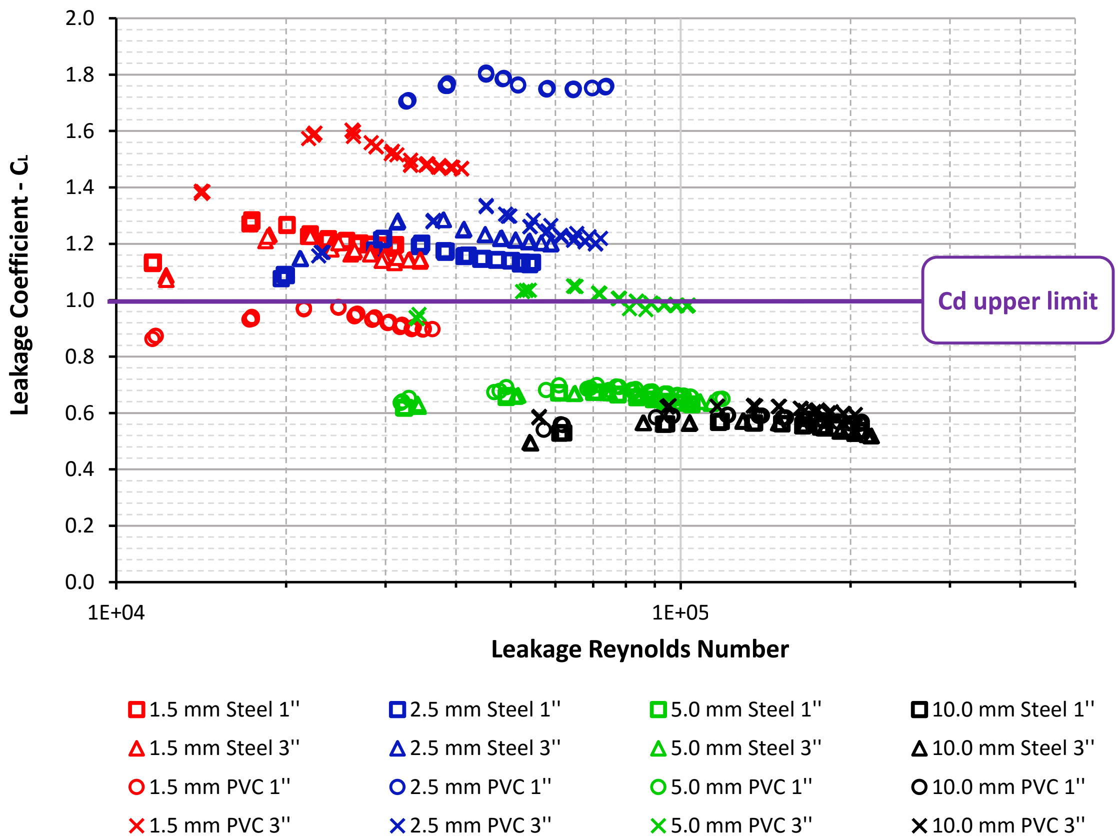

Figure 28 – Coefficient C_L obtained from experimental data

Figure 28 demonstrates differences addressed to the test groups, now related to the C_L coefficient. In this case, grater variations are highlighted for smaller orifice diameters. As before, smooth tendencies of the curves are observed with increasing of Reynolds number. Furthermore, the upper limit of the discharge coefficient is also highlighted in Figure 28, showing that similarities between C_L and C_d are lost when $N1 \neq 0.5$.

The C_L series standard deviation and maximum dispersion have been also performed, resulting in Table 9. The parameter standard deviation reached up to 4.4% and the maximum dispersion reach up 14.9%, being both presenting tendencies to decrease for larger orifice sizes. Like the exponent coefficient, C_L appears to be direct related to the orifice size, however its behavior is evidently different between small and large orifices. While for orifices diameters of $5.0\,mm$ and $10\,mm$ the coefficient assume stable values around 0.6 (what is expected in literature for C_d in turbulence flow through orifices), for both smaller diameters the behavior becomes very unpredictable reaching values up to 1.8, much higher than C_d limit ($C_d \leq 1.0$).

Table 9 – Statistical analysis of coefficient C_L

Orifice (mm)	C_L* | σ(%) | ψ(%)			
	Steel 1"	**Steel 3"**	**PVC 1"**	**PVC 3"**
1.5	1.21 | 3.3 | 12.8	1.16 | 3.6 | 13.7	0.93 | 3.5 | 12.3	1.50 | 4.1 | 14.9
2.5	1.15 | 2.9 | 12.4	1.22 | 3.2 | 11.4	1.76 | 1.4 | 5.80	1.24 | 3.8 | 14.3
5.0	0.65 | 2.8 | 8.80	0.65 | 2.3 | 7.70	0.67 | 2.5 | 9.40	1.00 | 3.1 | 11.6
10.0	0.55 | 2.2 | 7.50	0.54 | 4.4 | 14.8	0.58 | 2.3 | 9.10	0.61 | 2.3 | 7.40

* Values from Table 6.

In summary, the coefficients analysis have shown that unexpected variations occurs for the experimental ranges conditions.

Regarding to the discharge coefficient – C_d and the leakage coefficient – C_L (which bears similarities with the first), the parameter series presented in Figures 21 and 28 clearly demonstrates two distinct tendencies divided in approximately the middle of the 16 series. Such fact is similar to C_d behavior example from literature (Figure 5), what can be a change in flow regime, but in the case of experimental results the series peak have occurred for much higher Reynolds numbers.

The differences between coefficients values for smaller and larger orifices sizes, can also be related to the influence of viscous forces, since orifice area rapidly increase with its diameter. Additionally, the pipe materials and diameters also shows to affect the parameters behavior for small orifices. Thus, the assumption that leakage flows with greater effects of viscosity are more sensible to pipe roughness and initial velocity profiles, can justify the greater coefficients variations for smaller orifices. However, further efforts are still needed to fully understand this phenomenon.

In the other hand, the observed behavior for the exponent coefficient $N1$ was not previously related for round orifices. In special, values above $N1 = 0.5$ can not be justified by any relationship related in literature, with exception of assuming an area contraction with increase of pipes pressure ("negative elasticity effect"), what is very improbably in the case of round orifices. However, its stands out that since the power equation is an empirical relationship their coefficients are closely linked, the adoption of a fixed $C_L = 0.6$, for example, leads to all $N1 > 0.5$, but these are not the best coefficients to adjust the experimental data.

4.4 NEW FITTING FUNCTIONS TO EXPERIMENTAL DATA

Based on the widely use of the power equation 2.14, and their errors presented in previous section, a new empirical function was developed to improve leakage flows estimations for round roles under the experimental conditions adopted (Chapter 3). The new approach consists of dividing the pressure head range in two zones, since were observed two different behaviors in experimental data. For pressure heads below 25 m a logarithm function was used, while for upper pressure head values a new power function was adopted, presented in Equation 4.6, where Q_{leak} = leakage flow in m^3/s, Δh_{leak} = pressure head drop in the leak in m and χ_1, χ_2, ξ_1, ξ_2 are coefficients from the fitting equations:

$$Q_{leak} = \begin{cases} \chi_1 \, ln\left(\Delta h_{leak}\right) + \chi_2 & , \Delta h_{leak} \leq 25m \\ \xi_1 \, \left(\Delta h_{leak}\right)^{\xi_2} & , \Delta h_{leak} \geq 25m \end{cases} \tag{4.6}$$

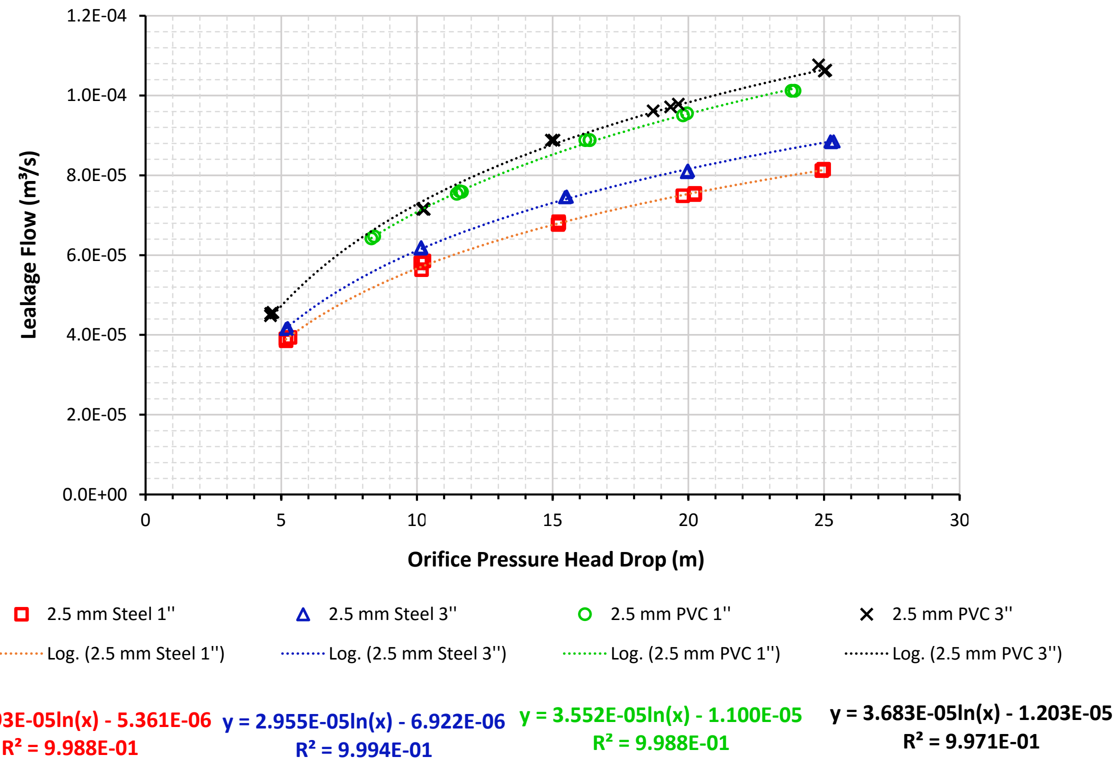

Figure 29 – Exemple of the logarithm function fitting in experimental data

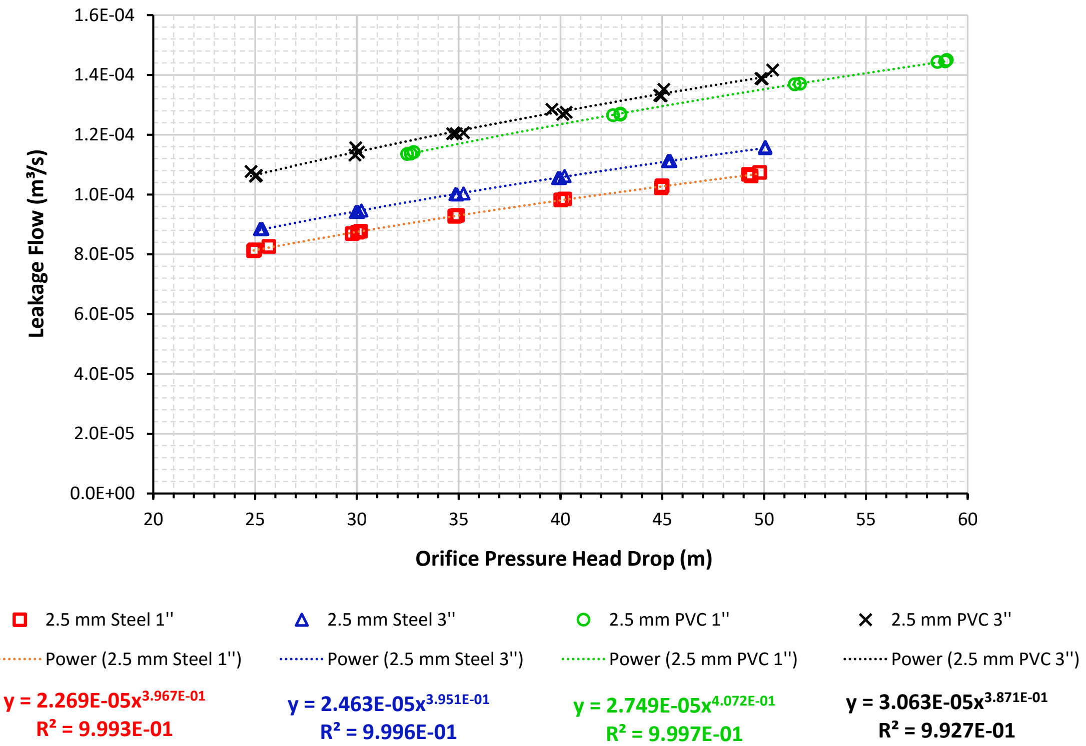

Figure 30 – Exemple of the new power function fitting in experimental data

The new equations fitting for the experimental data points is exemplified in Figures 29 and 30. The adjust of Equation 4.6 to experimental data points resulted in 16 values for each coefficient, presented in Tables 10 and 11.

Table 10 – Coefficients χ_1 and χ_2 ajusted to experimental data

Orifice (mm)	$\chi_1 \mid \chi_2$			
	Steel 1”	**Steel 3”**	**PVC 1”**	**PVC 3”**
1.5	9.11E-6 | -1.20E-6	1.05E-5 | -2.78E-6	1.15E-5 | -5.70E-6	1.22E-5 | -2.11E-6
2.5	2.69E-5 | -5.36E-6	2.96E-5 | -6.92E-6	3.55E-5 | -1.10E-5	3.68E-5 | -1.20E-5
5.0	1.13E-4 | -6.39E-5	1.21E-4 | -6.80E-5	1.08E-4 | -5.45E-5	1.00E-4 | -1.89E-5
10.0	4.44E-4 | -2.66E-4	4.78E-4 | -2.65E-4	4.35E-4 | -2.27E-4	4.05E-4 | -1.62E-4

Table 11 – Coefficients ξ_1 and ξ_2 ajusted to experimental data

Orifice (mm)	$\xi_1 \mid \xi_2$			
	Steel 1”	**Steel 3”**	**PVC 1”**	**PVC 3”**
1.5	8.081E-6 | 0.3861	8.577E-6 | 0.3967	8.863E-6 | 0.3936	1.047E-5 | 0.3893
2.5	2.269E-5 | 0.3967	2.463E-5 | 0.3951	2.749E-5 | 0.4072	3.063E-5 | 0.3871
5.0	7.643E-5 | 0.4298	7.859E-5 | 0.4440	7.425E-5 | 0.4350	8.072E-5 | 0.4108
10.0	2.646E-4 | 0.4678	3.188E-4 | 0.4378	2.633E-4 | 0.4709	2.817E-4 | 0.4439

Similarly to error analysis proposed in previous equations, the errors in leakage flows estimations were calculated by Equation 4.4, resulting in Figure 31. In contrast to previous analysis, the errors of the new function do not show explicit tendencies according to pressure head, what point to a better mathematical representation. The errors are significantly lower than the ones obtained from conventional equations. For the majority of data points the absolute error was kept below 2%. Higher errors just occurred for very low pressures, reaching values up to 8%.

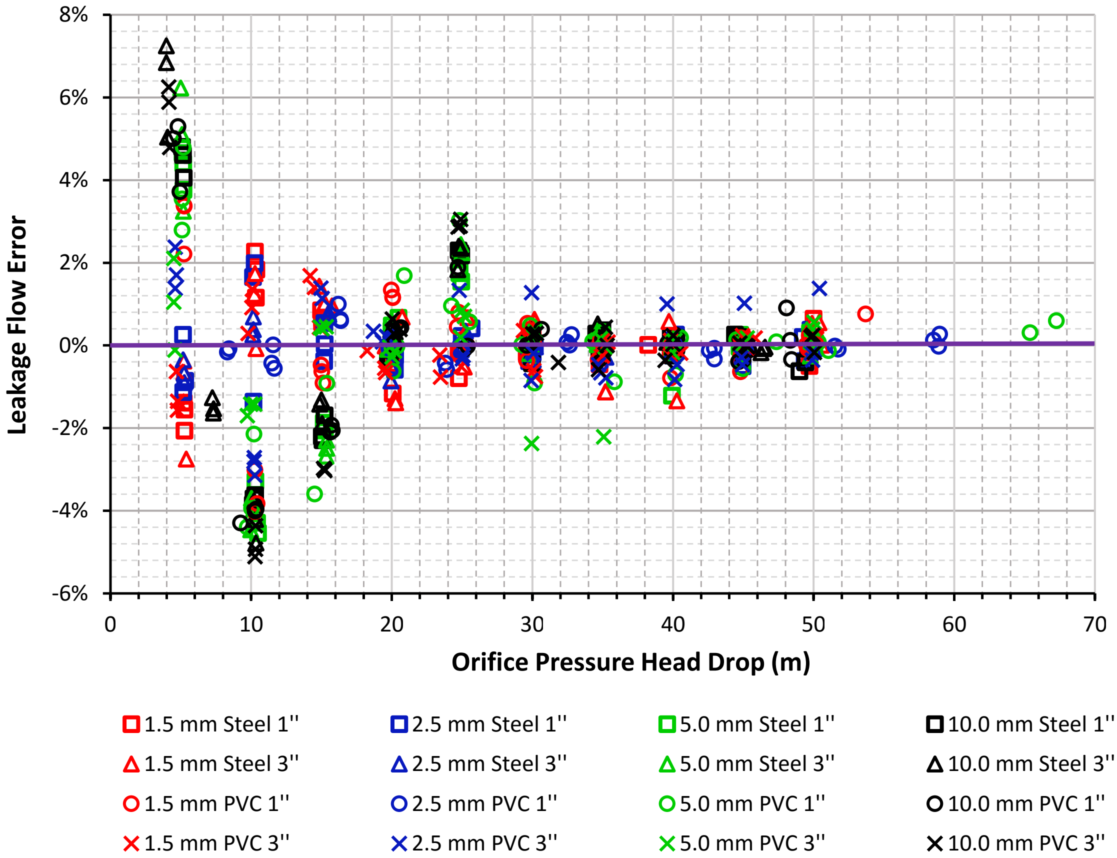

Figure 31 – Erros in leakage flow estimations with Equation 4.6

The use of a logarithm function for pressures head above 25 m seems to produce a significant improvement on the leakage flow estimations. Moreover, the adjusted coefficients for the power function (for pressure heads greater then 25 m) are significantly different than the previous observed values as consequence of the new fitting range. It is important to note that all coefficients still vary according to 16 test groups, and its use for distinct conditions must be better assessed.

4.5 SUMMARY OF THE CHAPTER

The experiments results for leaks through round roles in a complex pressurized system have shown consistent resemblance to literature reports, where leakage flows are commonly estimated by the orifice equation (WALSKI et al., 2009; FRANCHINI; LANZA, 2014). However, differences greater than the experimental setup uncertainty were found between the 16 test groups, pointing to the need of further investigations about the hydraulic characteristics of the leakage phenomenon. In such context, a detailed evaluation of the orifice and power equations was performed. Errors and coefficients behavior under tested leakage conditions were on focus of the analysis.

Possible influences of the pipes stretch elasticity in leakage phenomenon were sought by experimental data fitting with the FAVAD equation (Equation 2.17), but results found no influence of elasticity. The influence of pipes elasticity in the case of round roles was previously pointed as "very small" in literature (CASSA; ZYL; LAUBSCHER, 2010), hence the experimental data accuracy could be insufficient to account for those effects.

In conclusion, leakage phenomenon in small orifices can be affected by material and diameter of the pipe, because possible prevalence of viscous forces in the flow behavior appears to be more sensible to such characteristics. In contrast, larger orifices diameters have presented lower differences regarding pipes conditions.

Aiming to improve leakage flow estimations, the use of a logarithm function fit to experimental data was proposed and tested with promising results. The new method produced a significant reduction in errors when comparison to the orifice and power laws, allowing a better prediction of leakage flows for pressure head ranges from 5 to 50 m, using four new coefficients. The approach is still empirical, but points to a logarithm behavior between leakage flows and system pressure head for pressures above 25 m, instead of the traditional *power relationship*. However, further investigations must be carried out in order to link the new coefficients to leakage phenomenon characteristics, and consolidate a consistent relationship to represent leaks in WDS.

5 LEAKAGE IMPACTS IN WDS ENERGY EFFICIENCY

"It cannot be forget that in our system, water is the energy carrier. From this point of view leaks are both water and energy losses."

Cabrera et al. (2014)

Once leakage impacts on systems performance depend on individual WDS optimization and efficiency, evaluating them through laboratory experiments have required a complete analysis over system energy transformations. In previous reports, leakage experiments have been focused in *leakage flow* (GREYVENSTEIN; ZYL, 2007; WALSKI et al., 2004; FERRANTE et al., 2010), where most systems adopted consisted of a single pipe stretch, much simpler than a WDS, with no concerns about energy impacts.

The results of the leakage experiments have shown that the leakage flow affects mainly the demanded flow upstream the leak, while the pressure head variation between points downstream and upstream the leak are imperceptible. This effect is illustrated by Figures 32 and 33, which shows the relationship between the system flow and pressure head for points upstream and downstream the leak, respectively. In the first chart, the higher flows due to larger leaks are evident, while for the second, the system relationship between flow and pressure head its conserved.

The leakage, as any other system output, only affects the relationships between flows and pressures for upstream points, while this relation for downstream points is independent of previous outputs. The main effect of output flows for a compensated WSS (when increase in demands will be met by higher input flow) is that part of the flux hydraulic energy is decreased for every output, including leaks. Therefore, since the laboratory system was operated in order to met the leakage flow greater demands, preserving the downstream characteristics, the differences between the group tests results regarding the system energy use, points to the leakage impacts over the systems energy efficiency.

The analysis about leakage impacts in energy efficiency consisted of a full energy balance of the laboratory system, assuming *complete thermal equilibrium* and no *variations in flow internal energy*. Therefore, the system performance analysis consisted of quantify systems energy fluxes in different stages:

- Electric energy flux (W) input in hydraulic pumps.
- Hydraulic energy flux (W) input in the system (delivered by pumps).
- Hydraulic energy flux (W) losses by friction until the leak.

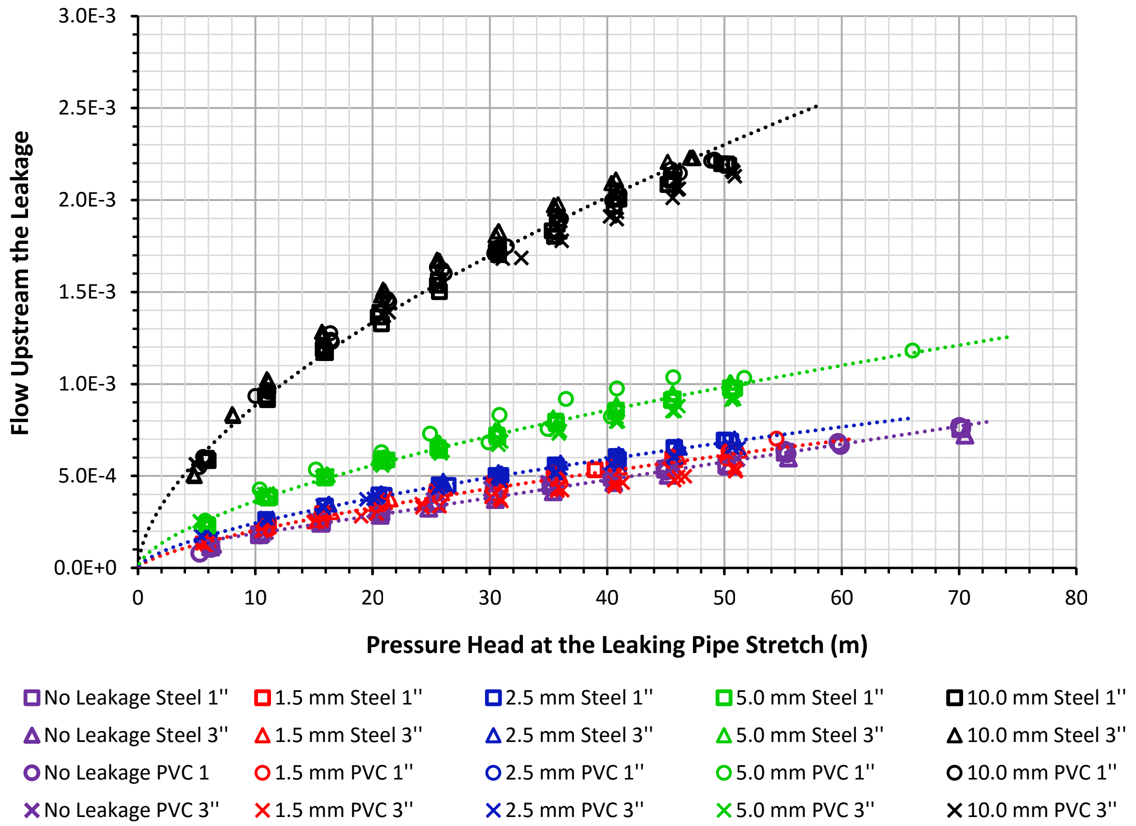

Figure 32 – System flow vs pressure upstream the leakage point

- Hydraulic energy flux (W) lost in the leak.
- Hydraulic energy flux (W) available downstream the leak.

Considering energy fluxes estimations, the leakage impacts were assessed under different perspectives. The present chapter aims to emphasize the existence and relevance of relationships between leakage and the energy use, based on acquired experimental data.

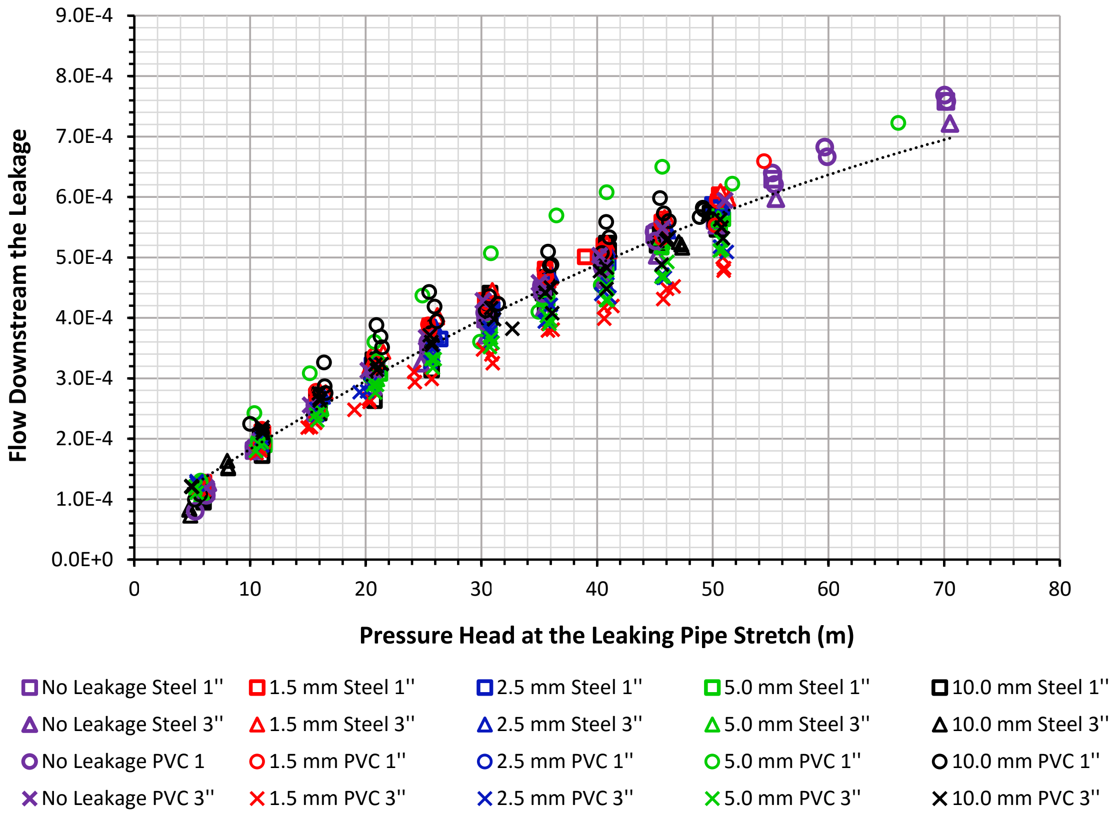

Figure 33 – System flow vs pressure downstream the leakage point

5.1 HYDRAULIC PUMP SYSTEM

The first step to accounting for the system energy use consist in evaluating the hydraulic pump system (two electrical motors and two hydraulic pumps in series) performance, which is the hydraulic energy input of whole system. In such a context, Figure 34 presents the hydraulic power delivered as function of electrical power consumption, for all leakage experiments. The differences between tested conditions are consequence of changes in pumps performance.

The hydraulic pump system total efficiency – η is the quotient between the hydraulic power delivered – E_0 (next to the pumps) and the electrical power consumed – E_{elec} (Equation 5.1). For the experimental tests, the parameter have shown to increase linearly with the pumped flows, but reaching very small values – up to 25% (Figure 35). This values points to discrepancies between pumps manufacturer characteristics and required operational conditions, used pumps have nominal flow of $10\,m^3/h$ with a full rotation ($\omega = 60Hz$), and all tests had lower pumped flows. Furthermore, the pumps inefficiency could be also motivated by the operation in series and lack of maintenance.

$$\eta\,(\%) = \frac{E_0}{E_{elec}} \tag{5.1}$$

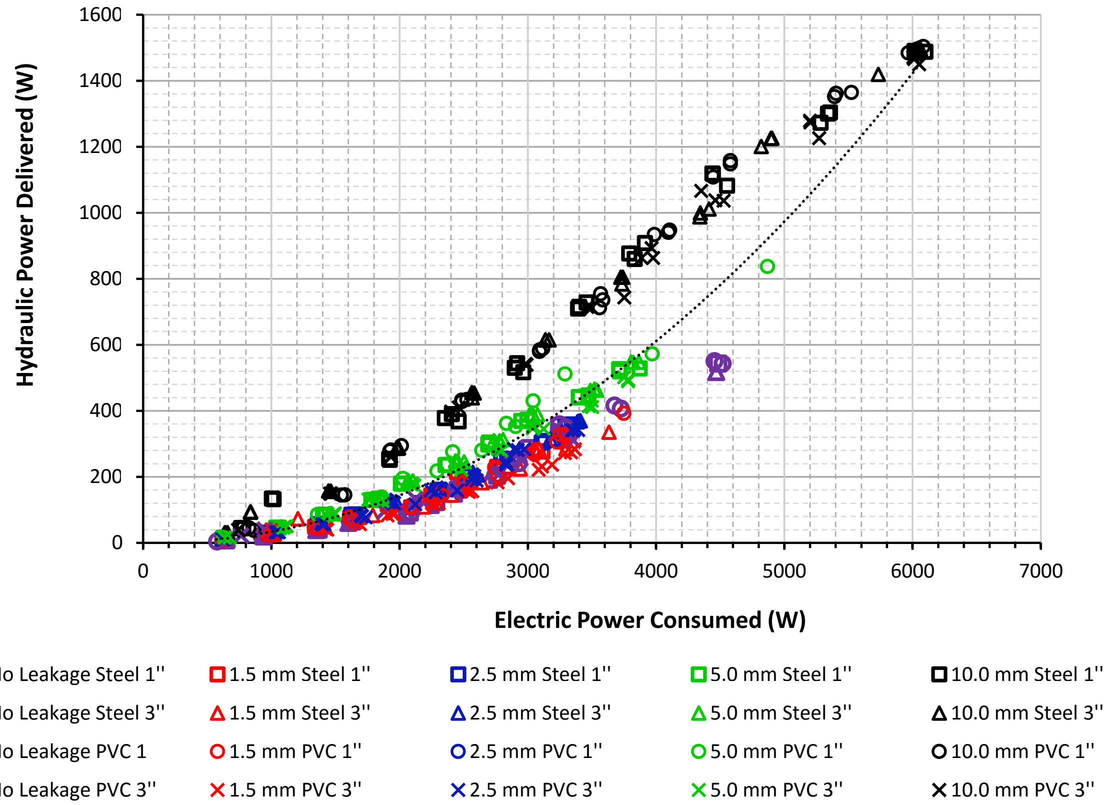

Figure 34 – Hydraulic power delivered by system pumps in fuction of electric power consuption

The large variation in pumps performance according to system input flows is a indirect consequence of leakage, motivated by the increase of demand flows. Since the pumps were operating in underflow conditions, the increase of flow have induced better efficiency in pumps, but if the leakage had caused an overflow condition the results would probably be the opposite.

The leakage flow impact in system demands is illustrated by Figure 36, which shows the leakage flow ratio $\xi_{Q_{leak},Q_{up}}$ as function of the leakage area ratio $\xi_{A_{orifice},A_{pipe}}$, which are given by Equations 5.2 and 5.3 respectively, where Q_{up} = flow upstream the leak, Q_{leak} = leakage flow, $A_{orifice}$ = orifice area and A_{pipe} = pipe cross-section area (FERRANTE et al., 2014).

$$\xi_{Q_{leak},Q_{up}} = \frac{Q_{leak}}{Q_{up}} \tag{5.2}$$

$$\xi_{A_{orifice},A_{pipe}} = \frac{A_{orifice}}{A_{pipe}} \tag{5.3}$$

High leakage flow ratio are consequence of low capacity of the laboratory system, due to small pipe diameters. Hence, apparently small orifices diameters for a "normal WDS"

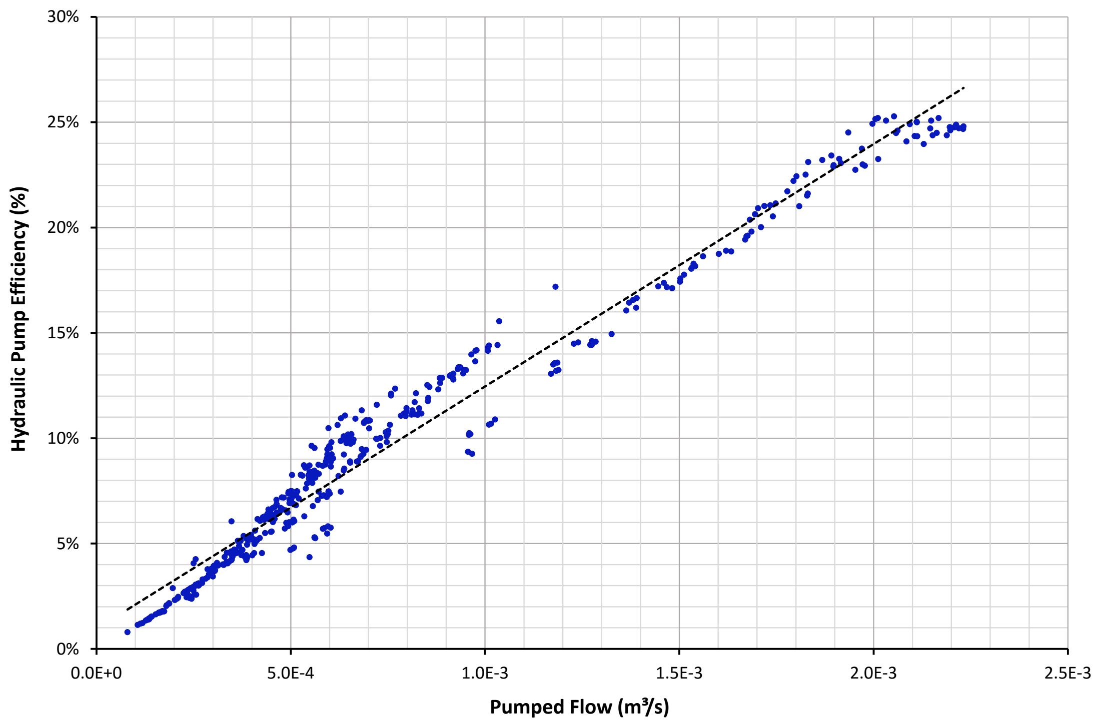

Figure 35 – Hydraulic power delivered by system pumps in fuction of electric power consuption

actually represent large leaks for the laboratory. In leakage experiments from literature, the flow that remain in the pipe after leakage is unreported, sometimes is null.

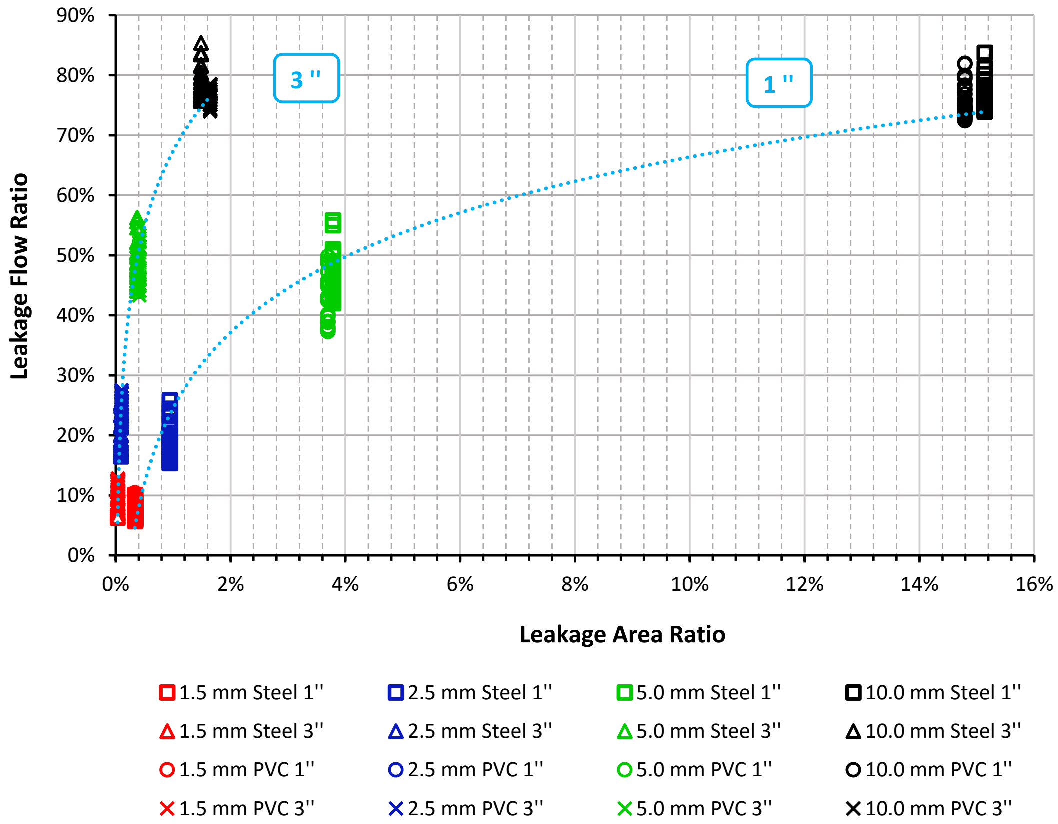

Figure 36 – Leakage flow ratio as fuction of leakage area ratio

Two distinct patterns are observed in Figure 36 according to pipe diameters, and their comparison shows that leakage flow ratios are not function of pipes area. Furthermore, the leakage flow ratio for the experiments vary from 10% to 80%, for a individual leak, thus leakage influence in pumped flows were significantly high. This scenario is comparable to real WDS in case of pipe bursts or summing up all real water losses (Table 1).

Pumps operation were performed by frequency inverters, which allows establishing different rotations and set distinct operational points for the systems, ensuring a better control over energy inputs. The operational point of the system is defined by the interception of the system curves and the pumps curves (MAYS, 2000). In the case of the leakage experiments, five distinct system curves resulted from distinct orifices diameters, which were evaluated next to the pumps output (Figure 37).

The combination of different pump curves for different rotation levels and the system curves defines all operational points performed in the leakage experiments, which together with the pump efficiency provides a complete picture of hydraulic pumps conditions (Figure 38). Small increments on pumps rotation have allowed a precise set of different system pressure heads, consequently changing the system operational point for each individual test. Pumps efficiency have not shown sensitivity to the distinct pump rotations adopted, what can be consequence of the underflow operation. Further investigations

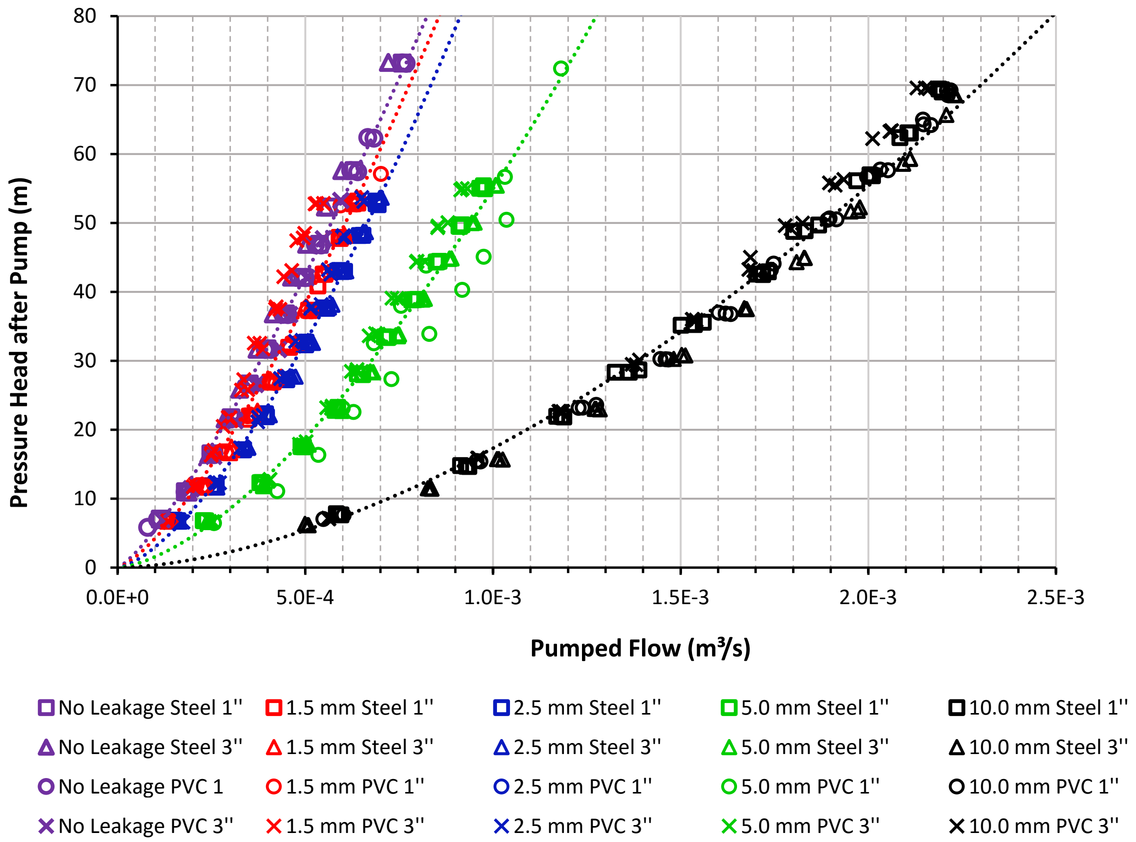

Figure 37 – System curves for the leakage experiments

must be placed to properly understand the hydraulic pumps performance over distinct operational conditions.

The chart of Figure 38 comprises all achievable operational points for the LENHS system for each level of leakage. Changing the hydraulic pump system rotation with frequency inverters its a powerful tool for a WSS, since the input of hydraulic energy can be modulated, thus providing a great control of the system behavior. However, is important to note that similar curves must be rebuild for each individual system, with individual hydraulic pump systems.

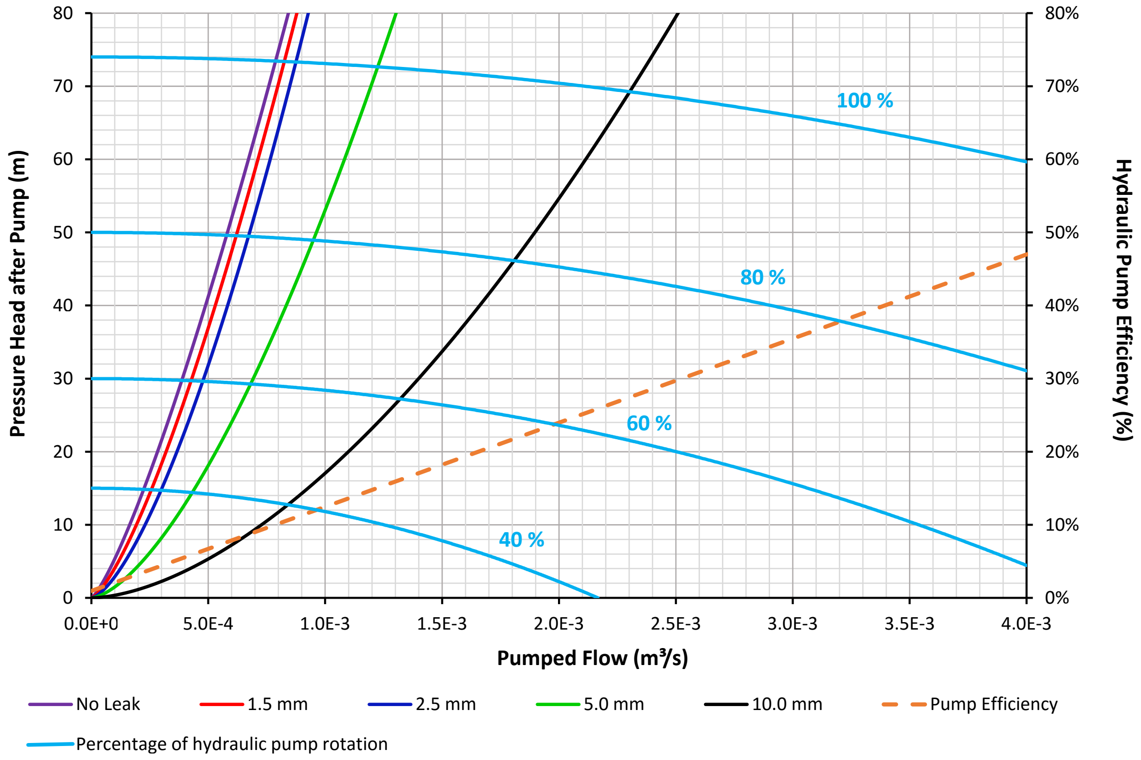

Figure 38 – System operational points for the leakage experiments

5.2 FRICTION ENERGY LOSSES

In the fate of pumped flow (water and energy source), until the tested leak, the system mass is preserved, but energy losses occurs by friction, which impacts the flows hydraulic energy in pressure form (MAYS, 2000). The difference from initial hydraulic power and its available portion upstream the leak is the total continuum losses by friction $F(Q_{up})$ (Figure 39).

The chart highlights a good relationship between the total power dissipated by friction and system pumped flows, what is expected from literature since friction head losses usually depends on flows square velocity, leading to a flow cubic order function according to total power dissipation (MAYS, 2000).

In order to estimate the portion of continuum losses related to leakage flows it is necessary deduct the losses referent to the same system without leaks (Equation 5.4), where E_f^{leak} = leakage continuum losses (W), $E_f(Q_{up})$ = continuum losses for the total pumped flow and $E_f(Q_{down})$ = continuum losses for the demand flow (total flow without leakage), as presented in Figure 40.

$$E_f^{leak} = E_f(Q_{up}) - E_f(Q_{down}) \tag{5.4}$$

The leakage friction losses presented similar relationships according to system

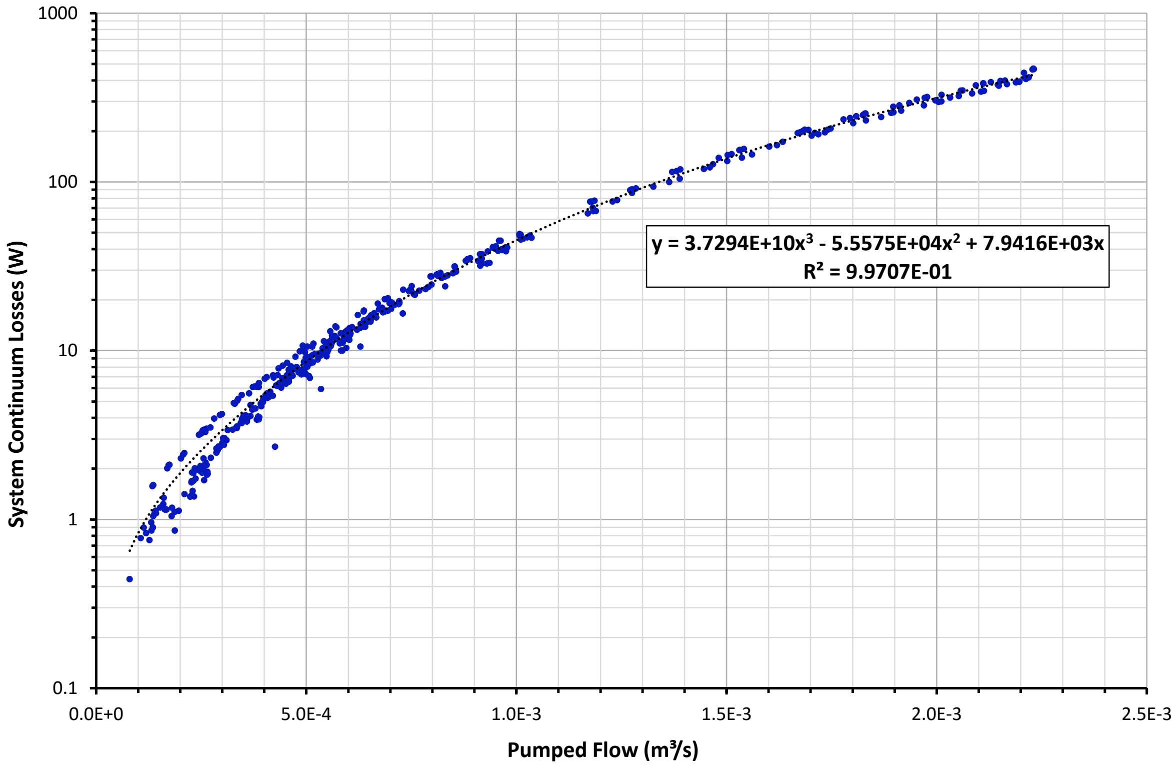

Figure 39 – System continuum losses in fuction of system flow

pumped flow, being their differences mainly related to different leakage flows, what was previously shown theoretically by Equation 2.31.

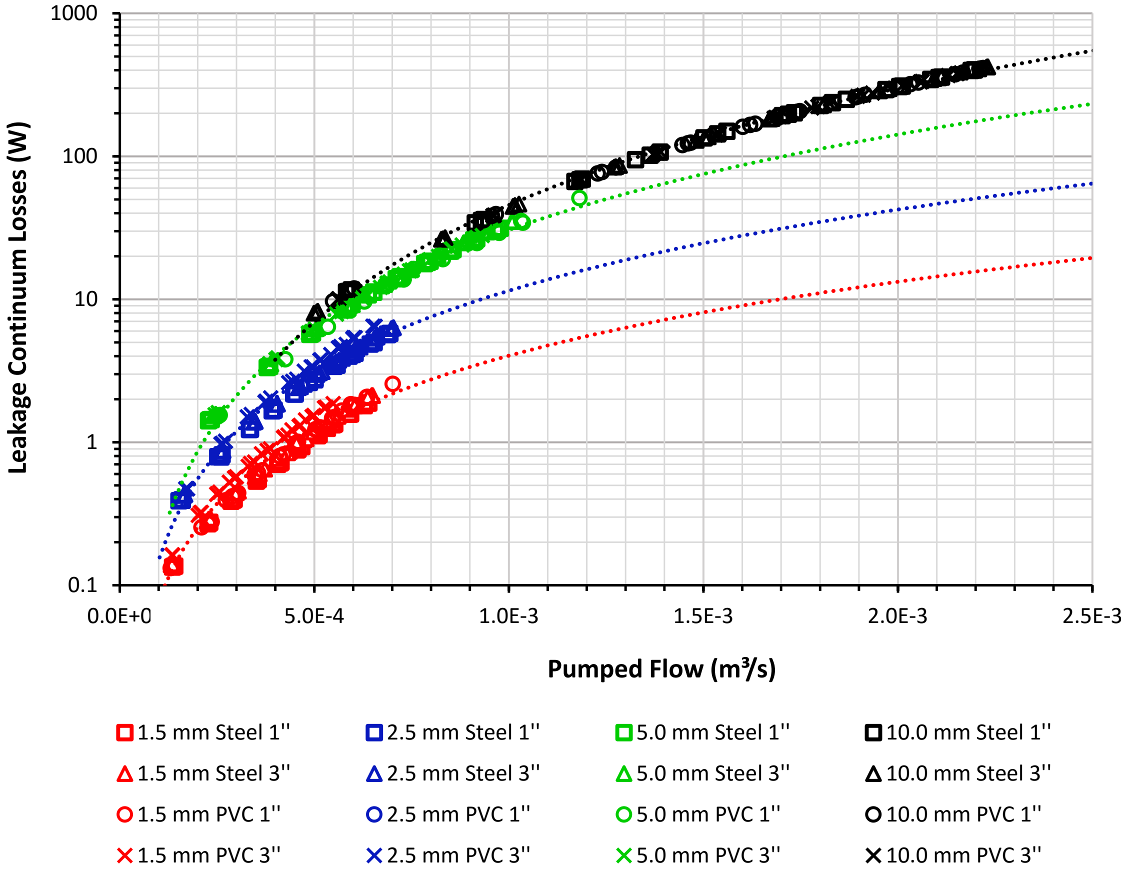

Figure 40 – Friction losses caused by leakage for the experimental tests

From another perspective, Figure 41 presents the leakage friction losses ratio $\xi_{E_f^{leak},H_0}$ according to initial hydraulic energy H_0 (Equation 5.5), as function of the leakage flow ratio $\xi_{Q_{leak},Q_{up}}$. The result shows an exponential increase of leakage friction losses ratio as function of the leakage flow ratio, where for the large orifices diameter almost 30% of the initial energy were dissipated by friction as consequence of leakage flows.

$$\xi_{E_f^{leak},H_0} = \frac{E_f^{leak}}{H_0} \tag{5.5}$$

The leakage friction losses ratio according to the electrical power consumed E_{elec} were also estimated (Equation 5.6), and results are presented in Figure 42. In contrast to previous one, this parameter depends on the hydraulic pump system performance, which vary significantly. Therefore, illustrating the increase of complexity in evaluating the energy use from a system in the case of misunderstandings energy transformations.

$$\xi_{E_f^{leak},H_{elec}} = \frac{E_f^{leak}}{H_{elec}} \tag{5.6}$$

In this case, the reduced values for the leakage continuum losses ratio is consequence of initial energy losses in the hydraulic pumps. Once more than 75% of the electrical

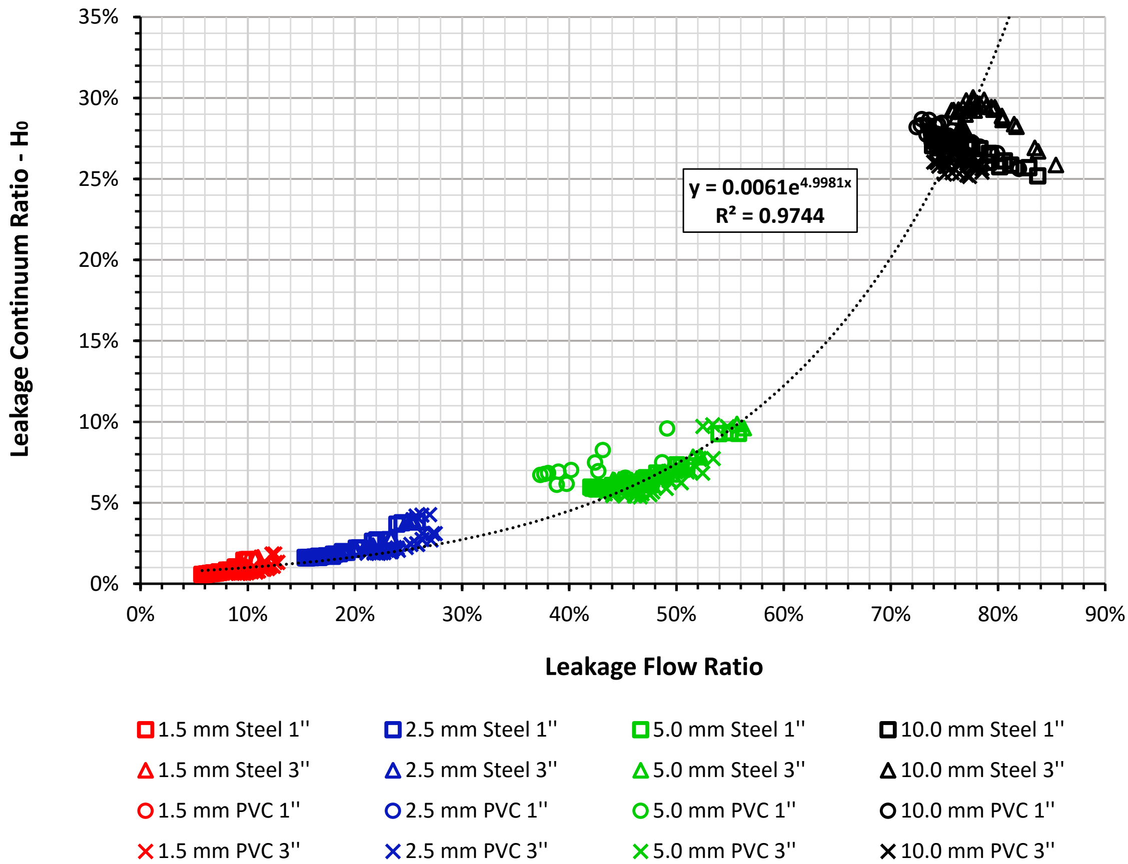

Figure 41 – Leakage friction losses ratio of initial hydraulic energy as function of leakage flow ratio

energy inputs were lost in pumping (Figure 35), further losses in hydraulic mechanical energy becomes proportionally smaller.

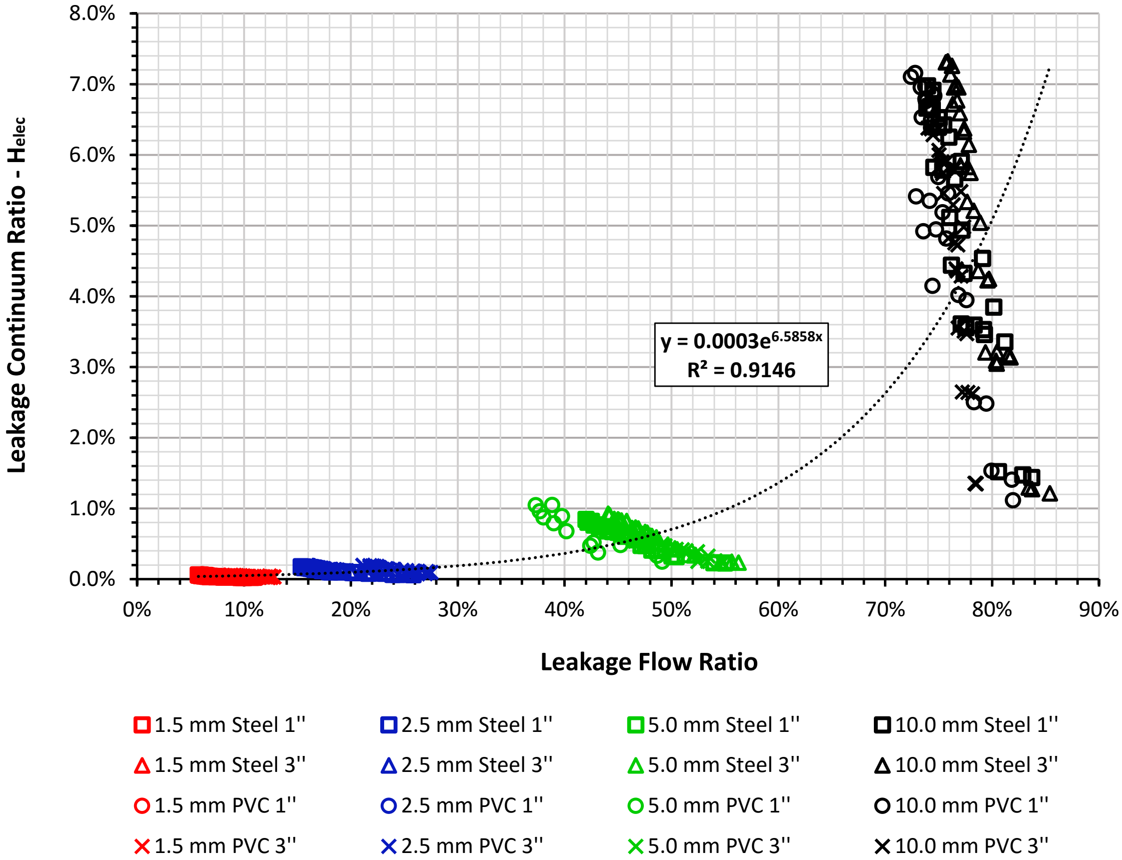

Figure 42 – Leakage continuum losses ratio of initial electrical energy as function of leakage flow ratio

5.3 LOCAL ENERGY LOSSES

The local energy losses addressed to the leakage phenomenon comprehend the total energy lost by the flux when passes through the leak point, calculated by the difference between upstream energy E_{up} and downstream energy E_{down} (Equation 2.28). Unfortunately, to precise quantify these losses for the leakage experiments the local energy dissipation E_{diss} must be evaluated using upstream, downstream and leakage flow conditions, and the pressure head differences measured between upstream and downstream sections were not enough accurate for this task. Furthermore, theoretical pressure differences disregarding energy dissipation have shown to be much lower than large dynamic oscillations of the laboratory system (Figure 13), what have also prevented a proper pressure measurements.

Therefore, the analysis of local energy losses at the leak point have assumed a constant pressure head in all leakage pipe stretch ($h_{up} = h_{down}$). Hence, all terms of the local energy balance (Equation 2.28) were estimated using equations 2.25, 2.26 and 2.27. The results for total local energy losses highlights an exponential increase as function of system pumped flows (Figure 43), reaching up to 1200 W for the 10.0 mm orifice diameters.

Local energy losses ratio according to the upstream power $\xi_{\Delta E_{leak}, E_{up}}$ (Equation

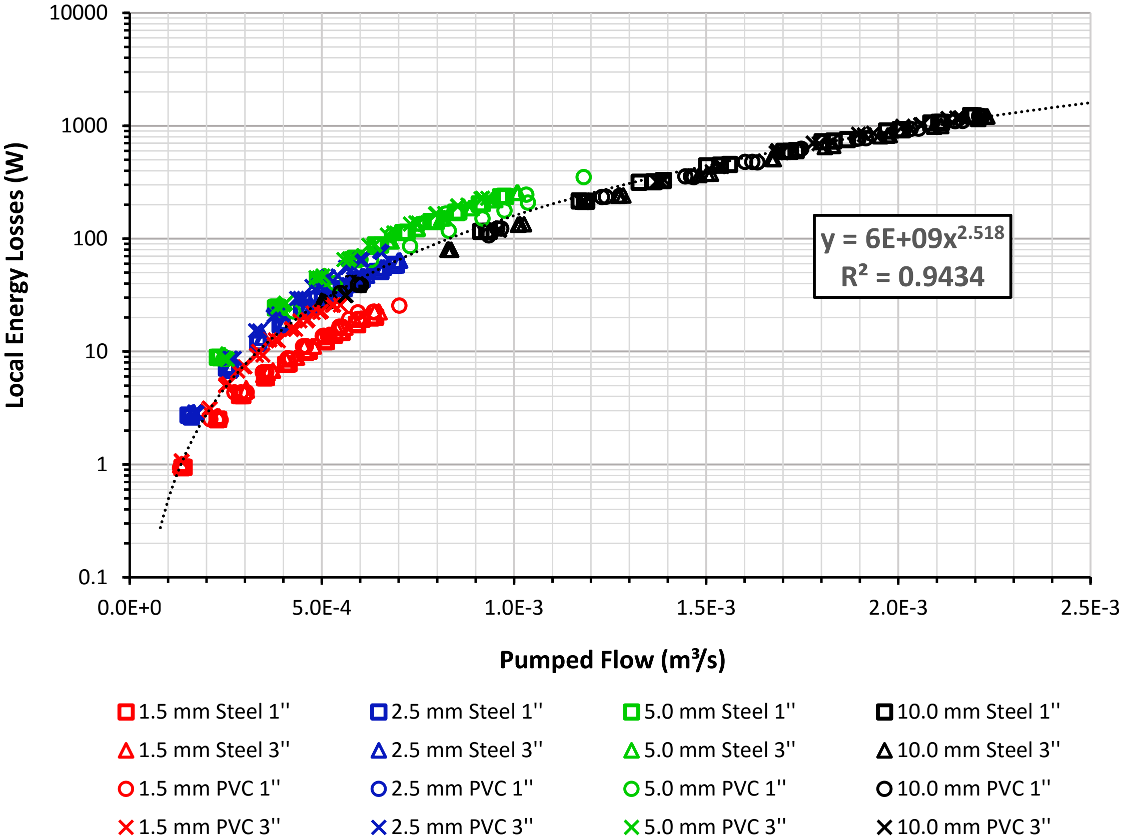

Figure 43 – Local energy losses at the leak point as function of system pumped flows

5.7, where E_{leak} = leakage jet hydraulic power (W), E_{diss} = local dissipated power (W), E_{up} = upstream leak hydraulic power (W) and E_{down} = downstream leak hydraulic power (W)) have shown that the proportion of energy lost was similar to the water lost, for the laboratory system (Figure 44). This result is not intuitive, and points to a proportional impact of magnitude between water losses and their consequent energy losses in a WDS. Aiming to investigate individually both parts of local energy losses, a deeper analysis about E_{diss} and E_{leak} are detailed in sequence.

$$\xi_{\Delta E_{leak}, E_{up}} = \frac{E_{up} - E_{down}}{E_{up}} = \frac{E_{leak} + E_{diss}}{E_{up}} \tag{5.7}$$

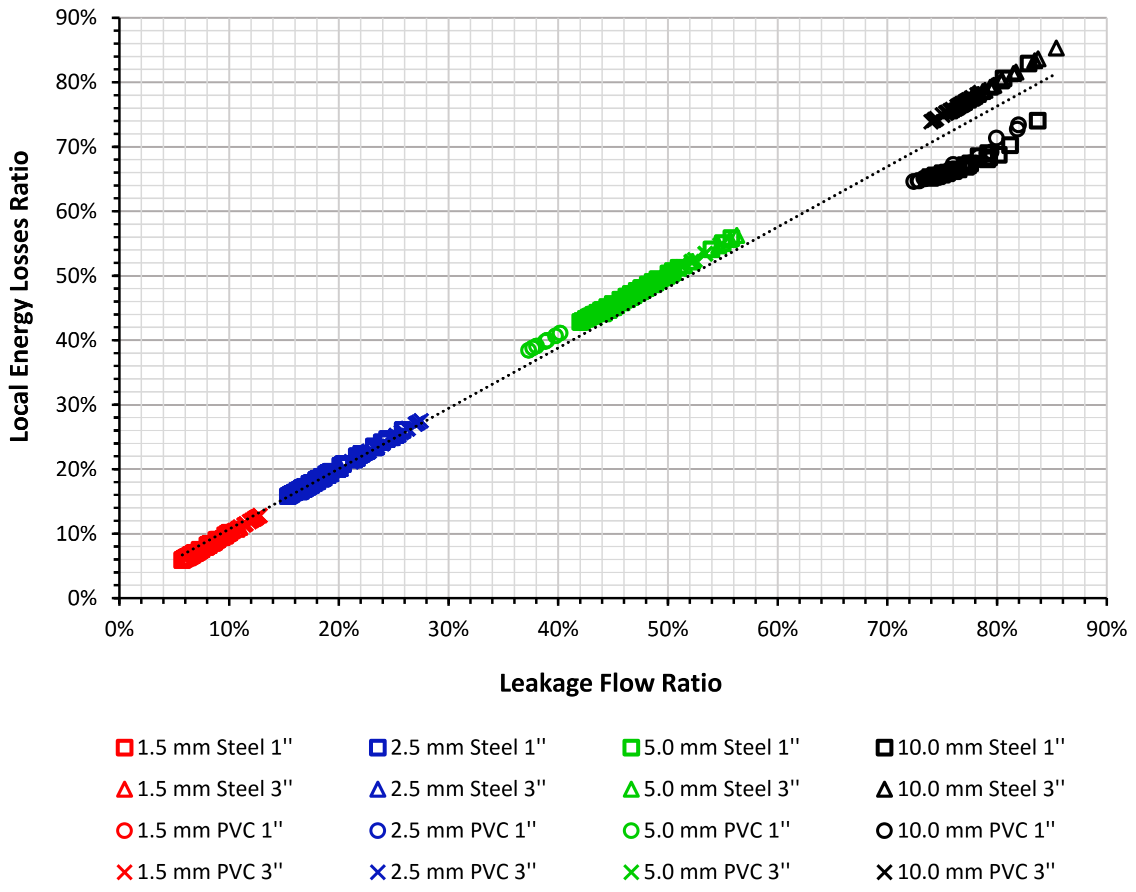

Figure 44 – Local energy losses ratio vs. leakage flow ratio

5.3.1 Leakage Hydraulic Power – E_{leak}

The hydraulic power of the leakage jet E_{leak} leaves the system as fluid mechanical energy, then is part of the local energy losses. Using Equation 2.27 with the experimental data, the leakage jet mechanical power were estimated for all tested conditions (Figure 45).

The chart of Figure 45 demonstrates that the amount of mechanical energy lost locally by the leak jet has the same order of magnitude that leakage continuum energy losses, for the laboratory system. In order to assess its magnitude in comparison to upstream hydraulic energy, the leakage hydraulic energy ratio $\xi_{E_{leak},E_{up}}$ were estimated by Equation 5.8, and presented as function of the leakage flow ratio $\xi_{Q_{leak},Q_{up}}$ in Figure 46.

$$\xi_{E_{leak},E_{up}} = \frac{E_{leak}}{E_{up}} \tag{5.8}$$

The results for leakage hydraulic energy ratio have shown different patterns regarding the orifices diameter, reaching up to 45% of the incoming hydraulic power of the flux. Moreover, for the smaller orifice diameters was observed a relative proportion between the water losses and energy losses, while in the case of both larger orifices the

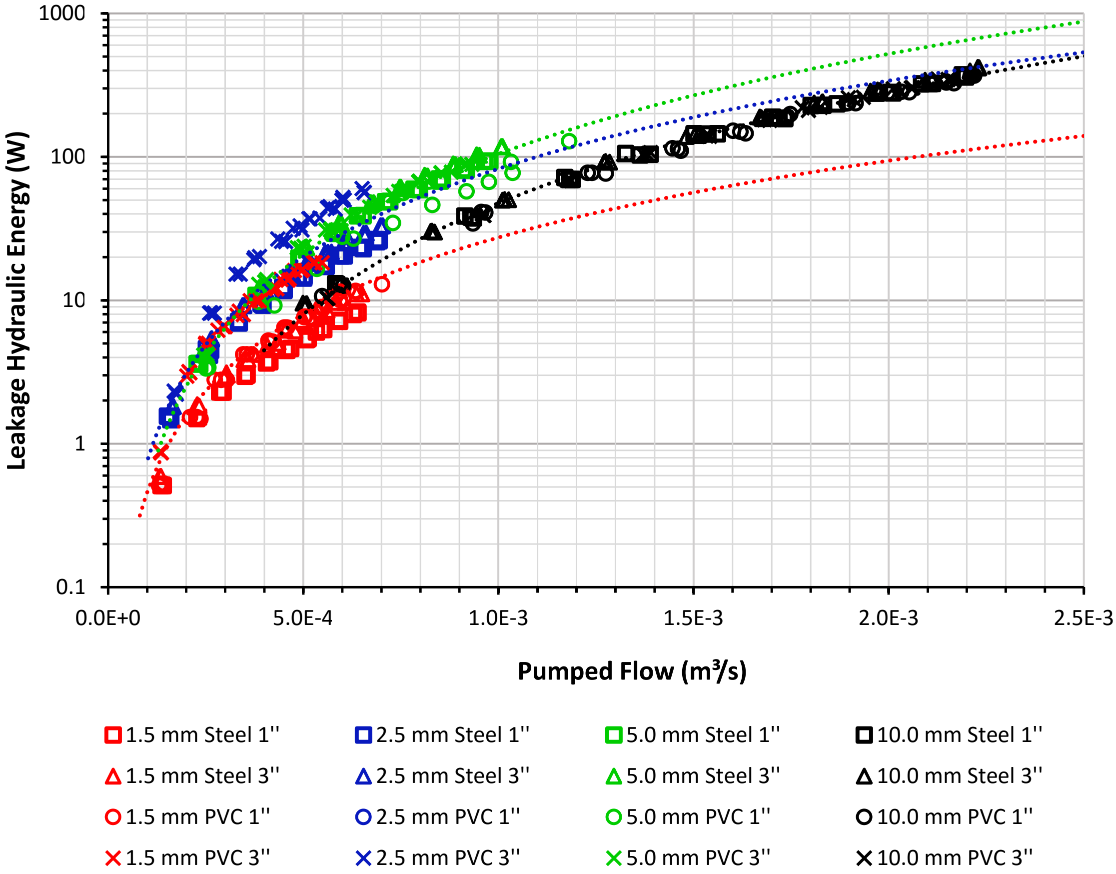

Figure 45 – Leakage hydraulic power as function of system pumped flows

water losses portion exceeded the energy one.

In addition, after leaving the pipe, the leakage jet hydraulic energy is rapidly dissipated in the surrounding water, and all flux kinetic energy decrease suddenly, being mainly dissipated by friction. In this context, higher leakage kinetic energy in the orifice exit have greater potential to erode soil surrounding pipes. For the leakage experiments a significant part of leakage hydraulic energy regards to kinetic form (Figure 47), being this relationship directly related to pipes external pressure head (in the case of external atmospheric pressure, the mechanic leakage flow would be completely kinetic).

In Figure 47 is highlighted the decrease of leakage energy kinetic portion for low velocities, which occurs for the lower pressure head tested.

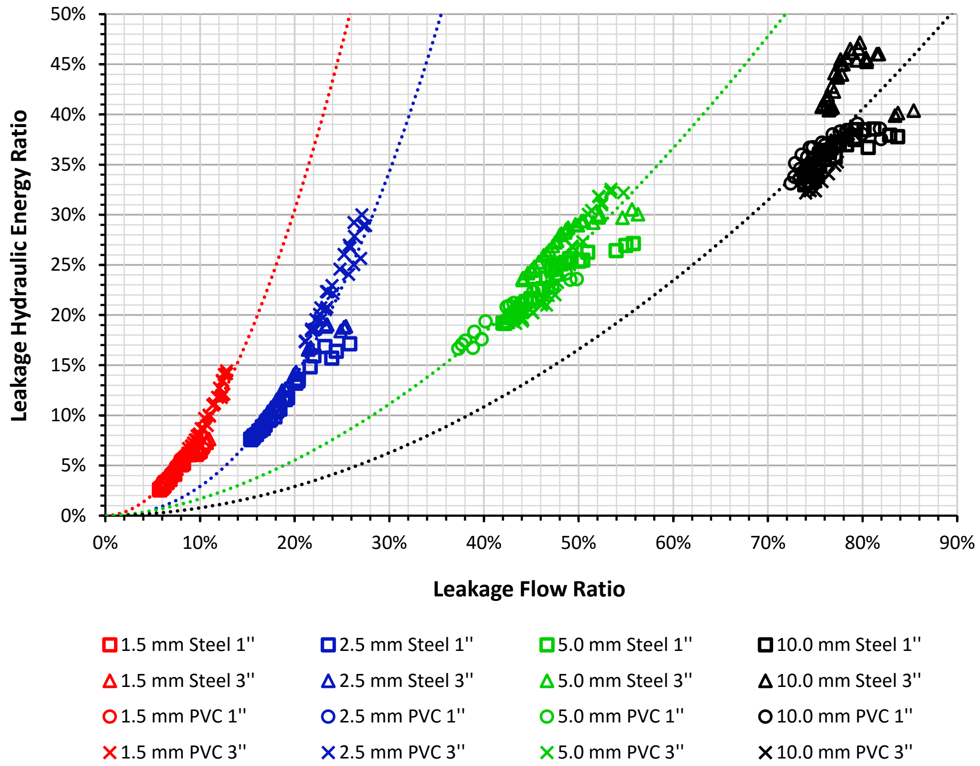

Figure 46 – Leakage hydraulic ratio as function of leakage flow ratio

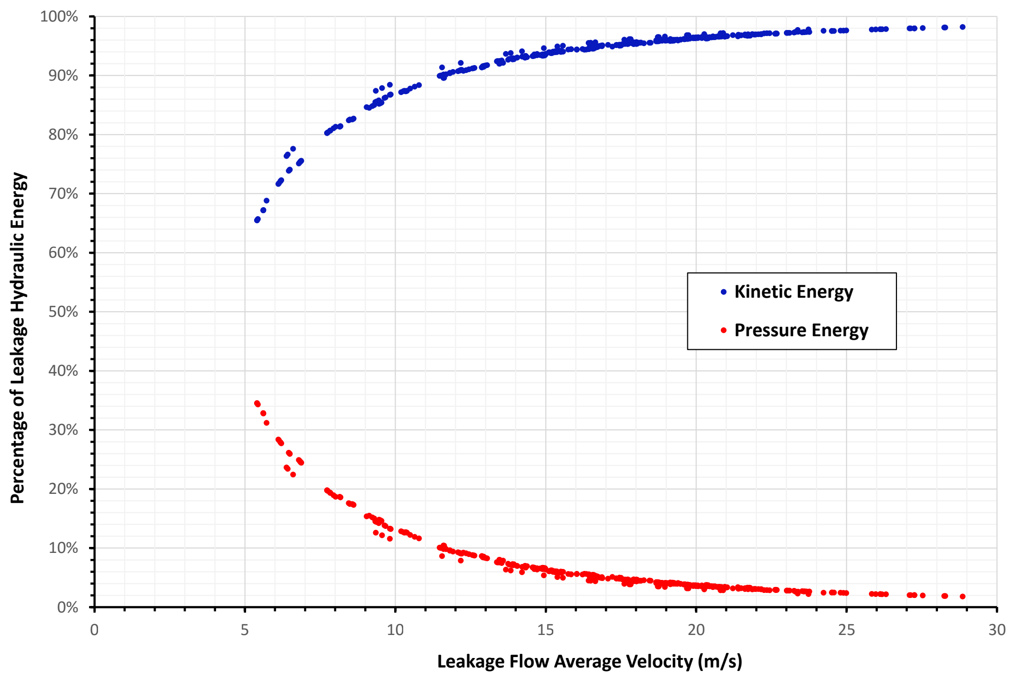

Figure 47 – Leakage hydraulic energy kinetic and pressure forms proportion

5.3.2 Local power dissipation by friction – E_{diss}

The portion of upcoming mechanical energy that does not result in leakage or downstream mechanic energy is necessarily dissipated by friction, which is intensified at the leak point by rapidly changes of velocity profile. Regarding this, the system dynamics and the low confidence in small differences of pressure measurements results in a poor comprehending about its behavior. Therefore, the following results aims to draw attention for this additional element for the local energy balance.

The local energy dissipation due to friction at the leak point results are presented in Figure 48. The chart shows both a higher values for the parameter, sometimes larger than the leakage continuum energy losses and a clear relationship between local dissipated energy and system pumped flows. The parameter appears to be insensible to orifice diameters, thus independently of the leak size, the disturbs in velocity profiles have caused similar energy dissipation.

The local dissipated energy ratio according to upcoming energy – $\xi_{E_{diss},E_{up}}$ were also estimated by Equation 5.9. The results (Figure 49) shown a linear relationship between the dissipated energy ratio and the leakage flow ratio. Moreover, negative values of dissipated energy ratio were also observed, indicating errors on the parameter estimations, probably due to the constant pressure head assumption for the leakage pipe stretch.

$$\xi_{E_{diss},E_{up}} = \frac{E_{diss}}{E_{up}} \tag{5.9}$$

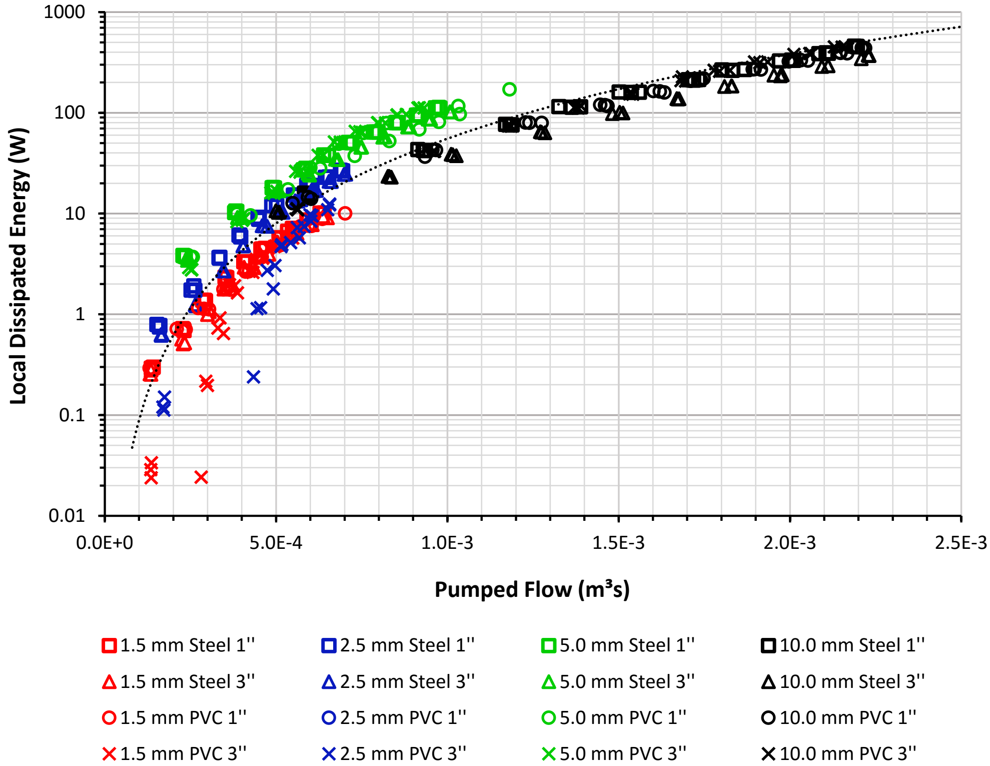

Figure 48 – Dissipated energy by friction at leakage point as function of system pumped flows

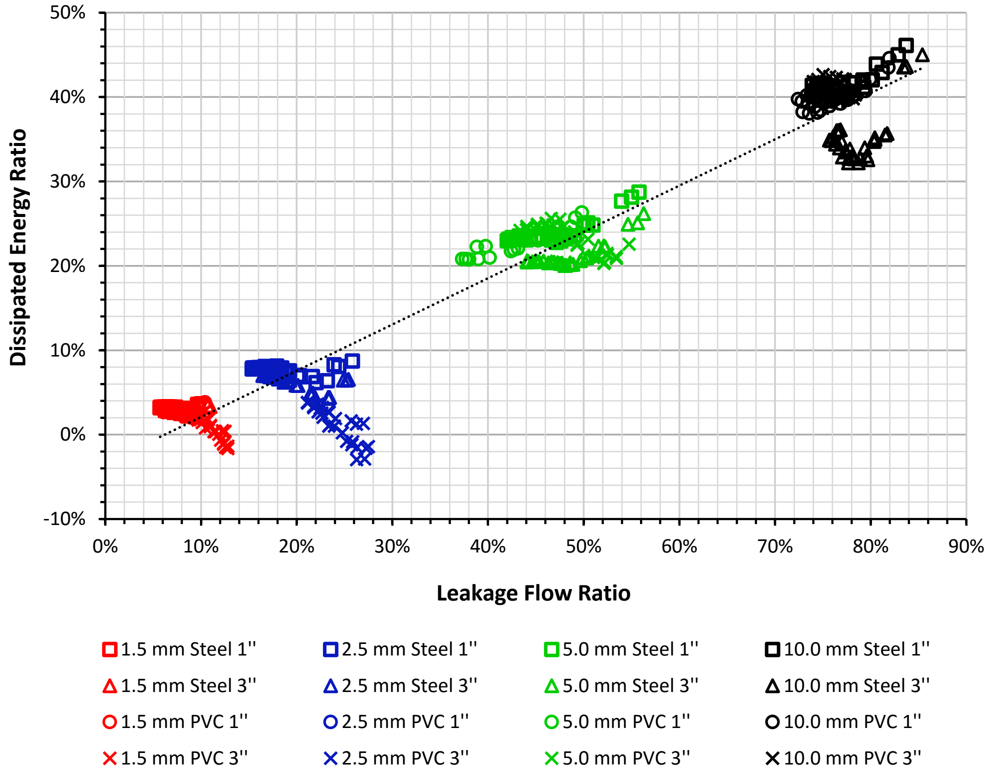

Figure 49 – Dissipated energy ratio as function of the leakage flow ratio

5.4 GLOBAL EFFICIENCY INDICATORS AND SYSTEM ENERGY BALANCE

The assessment of the system's total energy efficiency is challenging as consequence of distinct leakage impacts on system performance. In such a context, one form to evaluate the system energy efficiency regarding leakage consists in estimating the amount of energy required to pump $1\,m^3$ in the system, and compare the results for the same index accounting for the delivered demand (CABRERA et al., 2010). This analysis aims to contrast similar networks from the demands point of view for different levels of leakage, comprising all elements in the path between input of electrical energy and the delivered flow downstream the leak point. Hence, the respective indexes $\xi_{E_{elec},Q_{up}}$ and $\xi_{E_{elec},Qdown}$ are given by Equations 5.10 and 5.11, and the results are presented in Figures 50 and 51, where E_{elec} = total electrical power consumed (W).

$$\xi_{E_{elec},Q_{up}} = \frac{E_{elec}}{Q_{up}} \tag{5.10}$$

$$\xi_{E_{elec},Q_{down}} = \frac{E_{elec}}{Q_{down}} \tag{5.11}$$

The influence of hydraulic pumps performance becomes pronounced in Figure 50, because the increase in system flows by larger leaks induced a better efficiency of pumps and consequently the index decrease for greater leakage flows. A limited analysis regarding this index clearly shows that increase of system flows by leakage improve the system energy efficiency, due to better pumps operational point. However, contrasting Figures 50 and 51 shows that actually the energy required to supply system demands increase linearly for larger leakage flows, even with improvements in pumps efficiency. This differences are consequence of increasing in leakage energy losses, estimated here as continuum and local losses. Moreover, the small orifice diameters shown to have minimum impacts on this parameters.

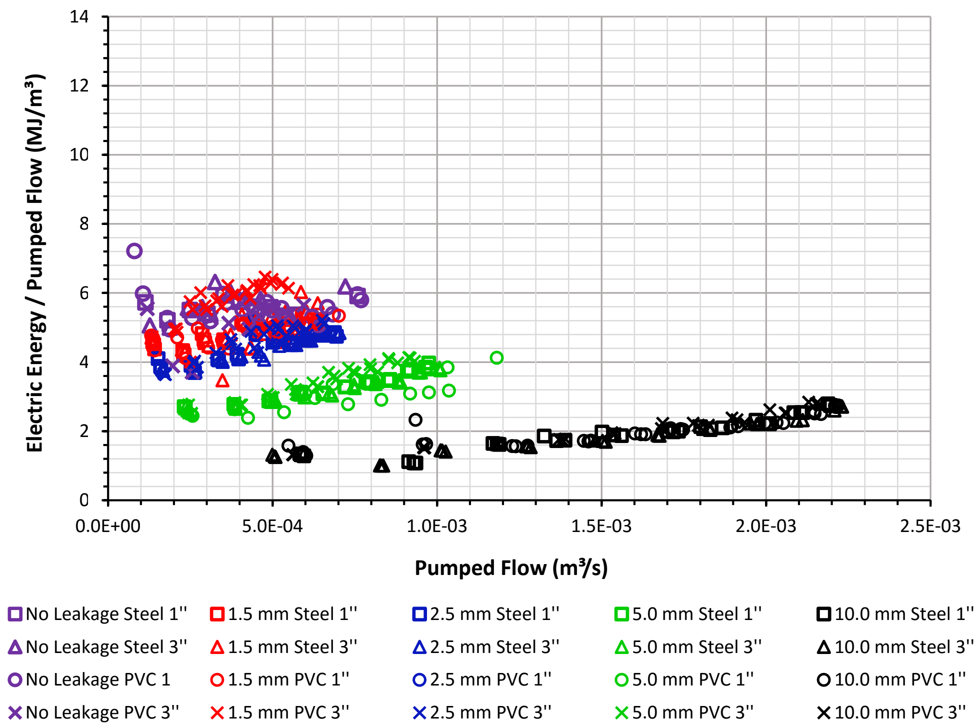

Figure 50 – Energy required for pump $1\,m^3$ of water into the system as function of system pumped flow

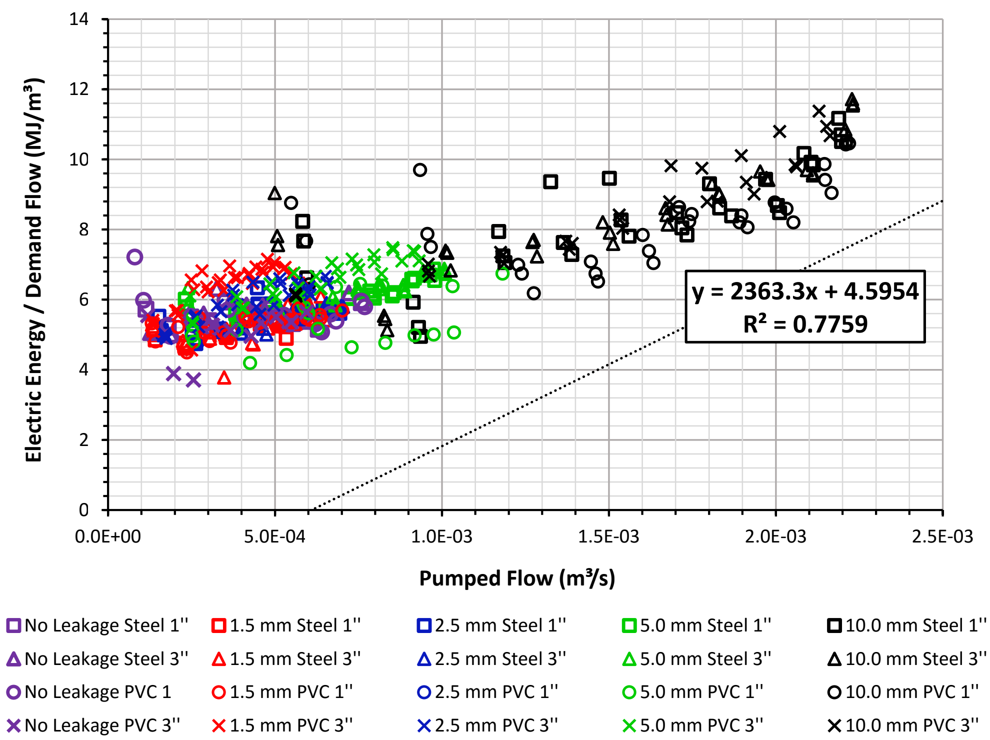

Figure 51 – Energy required for delivery $1\,m^3$ of water downstream the leakage as function of system pumped flow

The leakage impacts can also be assessed through an energy balance of whole system, but considering as starting point the initial hydraulic energy delivered from the hydraulic pumps – Equation 5.12, where E_0 = initial hydraulic power (W), $E_f^{no\,leak}$ = continuum losses without leakage (W), E_f^{leak} = leakage continuum losses (W), E_{leak} = leakage hydraulic power (W), E_{diss} = local dissipated power (W) and E_{down} = downstream leak hydraulic power (W). Hence, each term of the energy balance were estimated from the average of tested conditions separated by orifice diameters, resulting in Figure 52.

$$E_0 = E_f^{no\,leak} + E_f^{leak} + E_{leak} + E_{diss} + E_{down} \tag{5.12}$$

It were observed a constant hydraulic power downstream the leakage, a constant continuum losses for the *no leak* case and the increase of leakage associate energy losses according to the orifice diameters. Therefore, for all leakage experiments similar *demands requirements* were *supplied* but with distinct levels of leakage, all for the same system.

Figure 53 presents the same parameters, but proportional to the initial system hydraulic energy E_0. Hence, demonstrating the rapidly increase in total leakage energy losses for the larger orifices. The energy balance analysis demonstrates that there are different levels of influences for each type of leakage energy losses, being the leakage hydraulic power predominant for the smaller orifices, and leakage associated friction losses rapidly increasing for larger diameters.

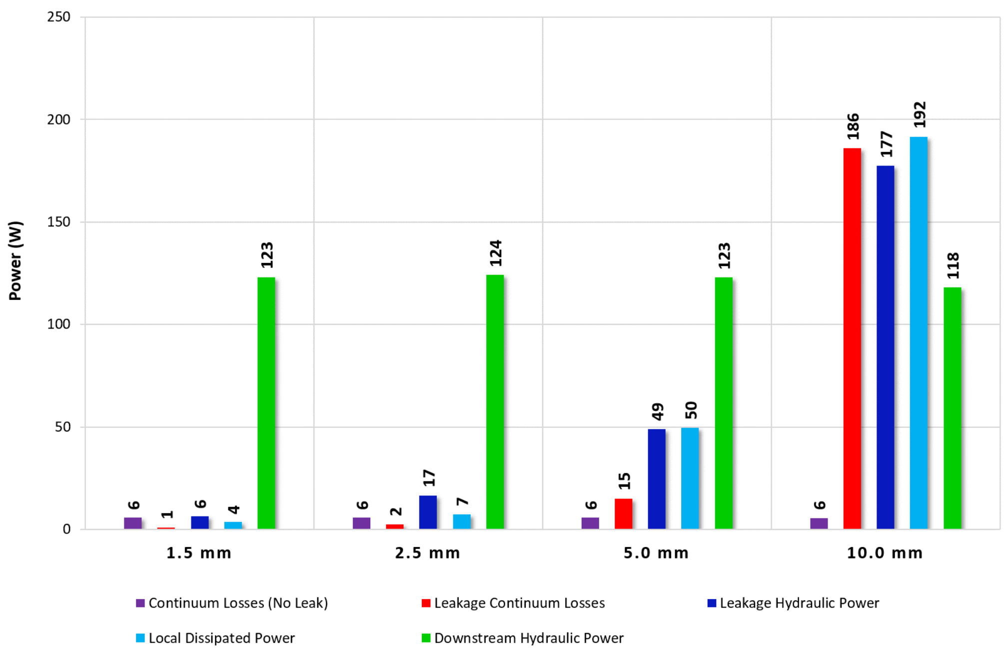

Figure 52 – System energy balance for the leakage experiments

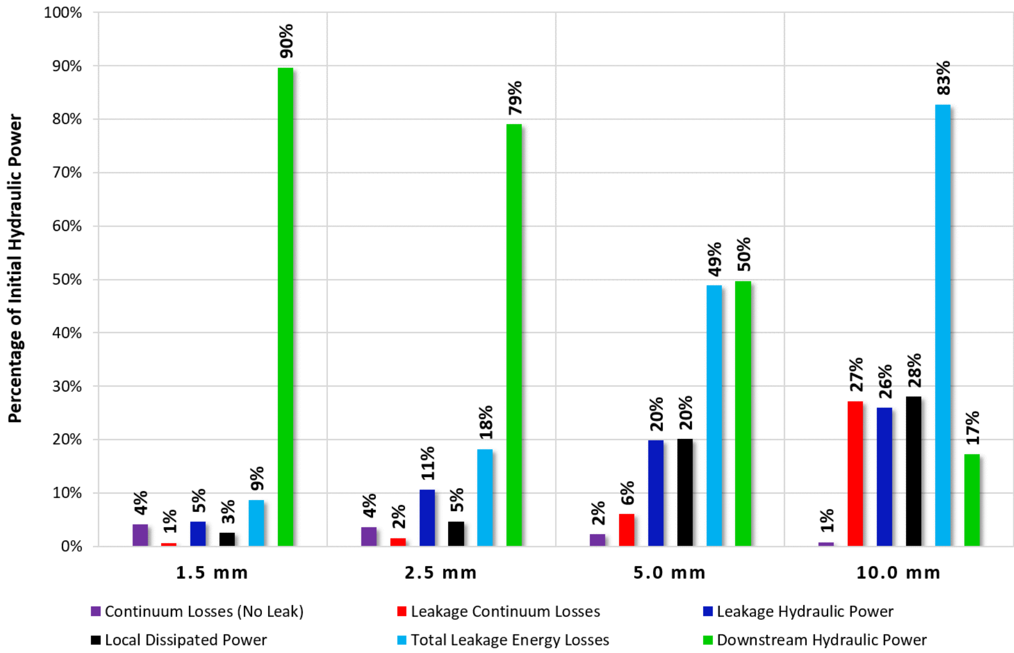

Figure 53 – System energy balance, proportional to initial hydraulic power, for the leakage experiments

5.5 SUMMARY OF THE CHAPTER

The laboratory experiments demonstrates that leakage phenomenons have caused energy losses to the system in the same proportion of water losses. However, further investigations about the energy losses shown evidences of complex mechanics involved in energy transformations.

Initially, the impacts of leakage over hydraulic pumps performance points to improvements in pumps efficiency, but the increase of system flows resulted in significant increase in continuum energy losses by friction. At the leak point two main sources of energy losses were identified: the hydraulic power of the leakage jet (which leaves the system) and local dissipated energy through friction, motivated by velocity profile disturbance. Hence, accounting for all energy losses associate to leakage, the overall efficiency of the system have shown to decrease, besides the volume of water lost.

It is important to note that the presented results were obtained in laboratory scale experiments, with considerable leakage proportions to system pumped flows. Hence, similar relationships must be properly evaluated in real WDS in order to account for leakage impacts in system energy usage.

6 FINAL REMARKS

"Globalization was supposed to break down barriers between continents and bring all peoples together. But what kind of globalization do we have with over one billion people on the planet not having safe water to drink?."

Mikhail Gorbachev

"The wars of the twenty-first century will be fought over water."

Ismail Serageldin

The experiment on leakage, herein performed in a laboratory scale, shows new evidences about leakage hydraulic behavior, not found previous studies, and allow the estimation of the systems energy balance associated to water losses. The laboratory setup differs from other experiments reported in literature by two main factors: the network complexity with energy source from hydraulic pumps (similar to real WDS) and the submerging structure built to ensure a better control over the leakage phenomenon.

Results regarding leakage flows estimations have identified small influences of pipe stretches materials and diameters, though the differences magnitude can not be explained by measurements uncertainties. The observed impacts of pipe stretch types in measured leakage flows were numerically similar, but when compared to the flow magnitude, revels greater sensitivity for the smaller orifice diameters. The analysis of results from each distinct pipe tested pointed towards the existence of consistent patterns in leakage flow for the distinct orifice diameters, suggesting that such differences are not errors, but influence of pipe characteristics in the leakage phenomenon. However, the low number of materials and pipe diameters tested prevented this experiments of identify correlations of this influence to pipes physical characteristics.

In respect to analytical equations for the estimation of leakage flows, detailed investigation about the *orifice* and *power equations* have shown that ideal adjustment coefficients can vary significantly according to the Reynolds number. Those adjustments includes the orifice diameter and the leakage flow dependence. The assumption of constant coefficients (for improving the equations applicability) have resulted in errors in leakage flow estimations, even for optimal values of the coefficients fitted to experimental data. Such errors reached up to 10% of the estimated leakage flow, and can be significant higher in the case of inadequate coefficients adoption.

Interestingly coefficient values for both equations were estimated from experimental data, highlighting elevated C_d values for smaller orifice diameters, C_L values greater than 1.0 and evidences of crescent $N1$ values from 0.41 to 0.55 according to orifice diameters, which was expected to be constant ($N1 = 0.5$). In addition, no influence of pipes elasticity were found in the experiments, which was also predicted by literature results for leakage through round orifices (CASSA; ZYL; LAUBSCHER, 2010). Therefore, the coefficients behavior were affected mainly by the leakage flow regime, represented by the leakage Reynolds number Such dependence is usually neglected in literature reports, which commonly assumes full developed turbulent flow conditions and constant coefficients.

Since the *orifice equation* is typically valid for turbulent flow conditions (IDELCHIK, 2003), and experimental results pointed to changes in flow regime for pressures head of $25\,m$, it was also proposed the use of a logarithm function for estimating of leakage flows for pressure head below $25\,m$. The new empirical equation duplicates the number of adjusting coefficients required if compared to the *power equation*, but the estimated errors in the best scenario are significantly reduced, being below 4% for almost all pressure range tested. Although this approach have a potential to improve the practical use of an empirical relationship between system pressure head and leakage flows, it does not brings any progress regarding leakage physical behavior.

It is important to reinforce that the improvement in the understanding about leakage hydraulics have the potential to enhance WDS models and associated field technology, what could benefit worldwide WDS management. Once many of World WDS presents leakage flows greater then 40%, small errors in leakage flow estimations can represent large amount of water, thus improvements in leakage modeling are still necessary.

Regarding the leakage impacts in WDS performance, the experimental results have shown evidences of decreasing in overall system energy efficiency according to greater leakage flows, which also means higher energy losses associated to leakage. Controversially, once the laboratory hydraulic pumps were operating in underflow conditions, the increase of leakage flows induced its better efficiency, but this advantage was not sufficient to overcome the continuum and local head losses, which increase exponentially according to leakage flow ratio. Results concerning the system operational point shows that leakage can affect system curves and consequently changes pumping requirements, which, in a situation of pumping overflows, would probably impact system pressures and demands.

A detailed analysis of the local leakage energy losses points to high dissipated energy by friction for the larger orifice diameters, which are evidence of great disturbance of velocity profile by the leakage phenomenon. Such dissipated power reached values similar to the leakage hydraulic power, that leaves the system in mechanical form. Moreover, the estimated leakage jet kinetic energy were also elevated, as consequence of leakage average velocities up to $25\,m/s$, the rapidly dissipation of such energy in soil justify the assumption of erosion in soil surrounding pipes.

The leakage flows performed in the laboratory experiments have consumed expressive amounts of energy, which were found to be proportional to the leakage flow ratio.

This energy implies in system inefficiency and additional costs, which are a significant part of the water losses problems in WDS. Therefore, the knowledge regarding leak is one of basic concepts missing for improve systems performance, with great potential to enhance the sustainability of water supply systems. Unfortunately, laboratory research is insufficient to reproduce similar operational conditions to real WDS, but can provide guidance in further efforts.

The development of extensive experiments regarding leakage through round orifices in a laboratory environment, has made it clear that analyzing and predicting leaks behavior is a hard task. Unexpected results, even when round orifices forms were adopted, points to unexplored mechanics aspects related to this complex phenomenon. In such context, the wide range of data and network information collected during the experiments was still insufficient to develop a *full description* of the leakage behavior.

The present study have shown that leakage can significantly depends on other system variables beyond the pressure, such as: flow regimes, pipe materials and soil characteristics. Therefore, the development of a more complete equation could result in a reliable relationship to precisely model leaks in most WDS. However, other possible scenario consists of individual system characteristics overcome local influence of leaks. In this case, leakage coefficients would be mainly determined by systems parameters, which will have to be evaluated individually, since WDS have an unique hydraulic behavior (COLOMBO; KARNEY, 2003). Currently, leakage behavior remains partially unpredictable in most systems, which hampers an efficient operation and causes losses for water facilities and produce environment impacts.

Regarding the water losses influence to the system performance, this research have proposed one possible methodology to estimates leakage energy losses, electing the pumping performance, and the continuum and local head losses as major factors associated to leakage energy losses. In the case of a real WDS, its performance can be affected by many other sources instead of just energy losses, thus distinct perspectives of leakage impacts can be placed.

Therefore, in order to develop sustainable water supply systems, saving water and energy, and prospect a reliable and robust infrastructure, more and better information must be acquired from operational systems. Concerning leakage, efforts in developing a database, linking leaks forms, flow and system conditions related, have great potential to improve future research, resulting in better actions to mitigate water losses. This thesis results presented evidences of great inaccuracy about leakage predictions according to misleading physical assumptions, and such fact is the consequence of underestimations in the complexity of leakage in WDS behavior.

6.1 LEAKAGE HYDRAULICS IN REAL WDS

As opposed to laboratory conditions, real WDS have a complex dynamic behavior, marked by demands patterns, multiple and unidentified leaks, transient flows and its uniqueness topology and constructional characteristics. In addition, most of World WDS are poorly monitored, and available informations regarding system operation (e.g. pressure, flow) are usually limited to a few of whole system nodes. Therefore, field studies related are intrinsically complex, hard and expensive.

In such context, were not found any literature reports about individual leaks investigation in real WDS. Some research have studied leaks in real WDS, but under wide perspectives, where leakage flows were estimated by indirect methods, and relationships developed covers whole system, what could be misunderstanding about specif physical mechanisms related to leaks. Hence, all knowledge about leakage in WDS, which is applied in hydraulic models and in water losses control programs, is grounded on theoretical and laboratory investigations on leak physics. However, it seems that several simplifications adopted in leakage modeling were no properly justified, because leakage estimations hardly reproduce its real behavior, even in laboratory conditions.

Once leakage have been part of WDS over many years, in significant proportions (40% of Brazil pumped flows PERTEL, 2014), systems hydraulic behavior is *familiarized* to leaks influence. In special, the leakage capacity of rapidly relieve systems hydraulic energy, according to pressure surges, can implies in an increase of WDS robustness, ironically. Thus, rapidly transients events, which can have destructive potential to cause system failure, could be mitigated by leakage (COLOMBO; KARNEY, 2003). Although the benefits of having leakage in a WDS probably do not overcome its cost impacts, this influences still requires better comprehension to ensure an efficient WDS management.

Further efforts addressing leakage research to real WDS appears to be the only way to understand its behavior in such a complex environment. Without reliable results in real operational conditions, applying leakage knowledge in WDS engineering solutions still implicates in high risk investments.

6.2 WDS PERFORMANCE

Regarding the relationship between leakage and WDS performance is important reinforce that energy losses are far away from exhaust possible leaks impacts. At the WDS *labyrinth* proposed by Colombo e Karney (2002) (Figure 2), important system characteristics in *performance neightborhood* have strong relationship with leaks, such as: deterioration, operating procedure and system failure. These connections between performance WDS characteristics and leakage are still incipient in WDS field research.

The pipes deterioration in WDS are probably one of the major source of new leaks. Greyvenstein e Zyl (2007), for example, have tested in laboratory failed steel pipe stretches, which leaking through corrosion roles. However, even with a high number of leakage repairs performed by water facilities, literature reports connecting deterioration aspects with pipes and leaks characteristics are practically inexistent.

In the case of leakage associations with operating procedure, highlights an important connection with pumping schedule and efficiency, which depends on demand requirements and topology aspects (COLOMBO; KARNEY, 2005). In such context, understand and distinct leakage from demands patterns is essential to optimizing WDS performance. The challenging regards to understand demands influence in system pressure (which is geographically heterogeneous) and further impacts in leakage flows, considering strong dependence of individual system topology.

6.3 WATER QUALITY IMPLICATIONS

Leakage in WDS can also impact the water quality in pipes network, since the passage of transient flows by the leaks could result in pipes negative pressures. In such events, the water surrounding the leaking pipe would be suctioned, as any contaminant present in the neighborhood soil. In order to evaluate related risks to final consumers several factors should be analyzed, such as: magnitude of transient events, leakage input flows, possible soil contaminants and its resilience to survive or reproduce inside the network. Moreover, as a preventive action, water facilities can also elect areas of greater risk for leakage occurrence, according to the soil usage conditions.

This subject represent an important connection between water quality issues in WDS, which can have direct influence of leakage. Unfortunately, research related is very incipient, and no experimental or field studies have been developed yet, what could be owing to difficulties of monitor consistently the occurrence of leakage and transients in WDS.

6.4 LABORATORY RESEARCH IMPROVEMENTS

The extensive laboratory experiments developed in this thesis have show unexpected behavior of leakage in WDS, a fact that raise a question: which would be the *appropriate way* to investigate the leakage phenomenon inside a laboratory? Once the researching subject – *leaks* is part of a complex system – WDS, performing simplified experiments in a laboratory scale could be as representative as the understanding of leakage connections with the whole WDS. In such a context, the lack of knowledge regarding leakage phenomenons in real WDS resulted in a wide range of distinct experimental approaches, which are hard to be compared and used to solve problems in real WDS.

Laboratory research are essentially necessary to provide a guidance for further investigations regarding a complex problem. However, since simplifications are adopted, experimental results will hardly reproduce with precision the real phenomenons. Regarding leakage in WDS, a hard, but important, task is to properly reproduce WDS dynamics. Moreover, concerns about pipes characteristics and surrounding soil can also improves the experimental setup, enhancing its resemblance with the occurrence of leakage in operational systems.

Lastly, an important remark about laboratory research consists of its ambiguity for engineering field, marked by a conflict of interests between *solve a practical problem* and *understand its physics mechanisms* (observed in leakage research regarding empirical relationships). The first, gather experimental approaches focused in establish relationships between useful variables, without necessarily grounding it is success to physical laws, what unfortunately turn difficult further advances. The second option inevitably includes the first, but goes much far beyond by developing tools for solve similar problems, and improving the knowledge regarding physical systems, being more costly than the first. In order to push knowledge boundaries, and produce more effective solutions of engineering problems, more efforts in the second option must be placed.

BIBLIOGRAPHY

ALEGRE, H. et al. *Performance Indicators for Water Supply Services*. 2. ed. [S.l.]: IWA, 2006. Cited in page 32.

BAILEY, N. D.; ZYL, J. E. van. Experimental investigation of internal fluidisation due to a vertical water leak jet in a uniform medium. In: *13th International Conference on Computing and Control for the Water Industry CCWI2015*. [S.l.]: Elsevier, 2015. v. 119, p. 111–119. Cited in page 52.

BEN-MANSOUR, R. et al. Computational fluid dynamic simulation of small leaks in water pipelines for direct leak pressure transduction. *Computers & Fluids*, Elsevier, v. 57, p. 110–123, 2012. Cited 2 times in pages 35 and 37.

CABRERA, E. et al. Energy assessment of pressurized water systems. *Journal of Water Resources Planning and Management*, ASCE, v. 141, n. 8, p. 04014095, 2015. Cited 5 times in pages 27, 28, 36, 37, and 46.

CABRERA, E. et al. *Towards an energy labelling of pressurized water networks*. [S.l.]: Elsevier, 2014. 209-217 p. Cited 2 times in pages 46 and 85.

CABRERA, E. et al. Energy audit of water networks. *Journal of Water Resources Planning and Management*, ASCE, v. 136, n. 6, p. 669–677, 2010. Cited 4 times in pages 28, 37, 46, and 102.

CASSA, A. M.; ZYL, J. E. van; LAUBSCHER, R. A numerical investigation into the effect of pressure on holes and cracks in water supply systems. *Urban Water Journal*, Taylor & Francis, v. 7, n. 2, p. 109–120, 2010. Cited 7 times in pages 28, 29, 37, 41, 44, 84, and 108.

CATALDO, A. et al. Experimental validation of a tdr-based system for measuring leak distances in buried metal pipes. *Progress In Electromagnetics Research*, EMW Publishing, v. 132, p. 71–90, 2012. Cited in page 35.

CHIS, T. Pipeline leak detection techniques. *Annals. Computer Science Series*, v. 5, p. 25–34, 2007. Cited in page 35.

COLOMBO, A.; KARNEY, B. W. Pipe breaks and the role of leaks from an economic perspective. *Water Science & Technology - Water Supply*, IWA PUBLISHING, v. 3, n. 1/2, p. 163–170, 2003. Cited 6 times in pages 31, 33, 34, 46, 109, and 110.

COLOMBO, A. F.; KARNEY, B. W. Energy and costs of leaky pipes: Toward comprehensive picture. *Journal of Water Resources Planning and Management*, ASCE, v. 128, n. 6, p. 441–450, 2002. Cited 8 times in pages 28, 31, 33, 35, 36, 46, 48, and 110.

COLOMBO, A. F.; KARNEY, B. W. Impacts of leaks on energy consumption in pumped systems with storage. *Journal of water resources planning and management*, ASCE, v. 131, n. 2, p. 146–155, 2005. Cited 5 times in pages 27, 36, 37, 46, and 111.

FERRANTE, M. et al. Leak size, detectability and test conditions in pressurized pipe systems: How leak size and system conditions affect the effectiveness of leak detection techniques. *Water resources management*, Springer, v. 28, p. 4583–4598, 2014. Cited 7 times in pages 29, 35, 36, 37, 41, 52, and 88.

FERRANTE, M. et al. Leakage and pipe materials. In: ASCE. *Water Distribution Systems Analysis 2010*. [S.l.], 2010. p. 1140–1145. Cited 4 times in pages 35, 42, 52, and 85.

FERRANTE, M.; MENICONI, S.; BRUNONE, B. Local and global leak laws. *Water resources management*, Springer, v. 28, p. 3761–3782, 2014. Cited 2 times in pages 43 and 61.

FRANCHINI, M.; LANZA, L. Use of torricelli's equation for describing leakages in pipes of different elastic materials, diameters and orifice shape and dimensions. In: *16th Conference on Water Distribution Systems Analysis, WDSA 2014*. [S.l.]: Elsevier, 2014. v. 89, p. 290–297. Cited 4 times in pages 41, 42, 52, and 83.

GIUSTOLISI, O.; LAUCELLI, D.; BERARDI, L. Operational optimization: Water losses versus energy costs. *Journal of Hydraulic Engineering*, ASCE, v. 139, p. 410–423, 2013. Cited in page 36.

GOULET, J. A.; COUTU, S.; SMITH, I. F. Model falsification diagnosis and sensor placement for leak detection in pressurized pipe networks. *Advanced Engineering Informatics*, v. 27, p. 261–269, 2013. Cited 2 times in pages 35 and 36.

GREYVENSTEIN, B.; ZYL, J. van. An experimental investigation into the pressure leakage relationship of some failed water pipes. *Journal of Water Supply: Research and Technology - Aqua*, v. 56, n. 2, p. 117–124, 2007. Cited 5 times in pages 37, 41, 52, 85, and 111.

GUO, S. et al. Two-dimensional pipe leakage through a line crack in water distribution systems. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering*, JZUS, v. 14, n. 5, p. 371–376, 2013. Cited 2 times in pages 45 and 52.

IDELCHIK, I. *Handbook of Hydraulic Resistance*. 3. ed. [S.l.]: JAICO Publishing House, 2003. Cited 5 times in pages 40, 41, 42, 43, and 108.

KUNDU, P. K.; COHEN, I. M.; DOWLING, D. R. *Fluid Mechanics*. 5. ed. [S.l.]: Elsevier, 2012. Cited in page 40.

LAMBERT, A. What do we know about pressure-leakage relationships in distribution systems. In: *IWA Conf. n Systems approach to leakage control and water distribution system management*. [S.l.: s.n.], 2001. Cited 4 times in pages 33, 36, 42, and 43.

LIJUAN, W.; HONGWEI, Z.; HUI, J. A leak detection method based on epanet and genetic algorithm in water distribution systems. In: *Software Engineering and Knowledge Engineering: Theory and Practice*. [S.l.]: Springer, 2012. p. 459–465. Cited in page 35.

LIU, Z.; KLEINER, Y. State of the art review of inspection technologies for condition assessment of water pipes. *Measurement*, Elsevier, v. 46, n. 1, p. 1–15, 2013. Cited in page 35.

MAYS, L. W. *Water Distribution Systems Handbook*. [S.l.]: McGraw Hill, 2000. Cited 7 times in pages 27, 37, 46, 48, 61, 90, and 91.

PÉREZ, R. et al. Methodology for leakage isolation using pressure sensitivity analysis in water distribution networks. *Control Engineering Practice*, Elsevier, v. 19, n. 10, p. 1157–1167, 2011. Cited in page 35.

PERTEL, M. *Experimentos Hidráulicos Conjugados ao Uso de Indicadores de Desempenho Aplicados à Quantificação de Perdas em Sistemas de Abastecimento de Água no Brasil*. Tese (Doutorado) — UFRJ, COPPE, Rio de Janeiro, Brasil, 2014. Cited 2 times in pages 33 and 110.

PUUST, R. et al. A review of methods for leakage management in pipe networks. *Urban Water Journal*, Taylor & Francis, v. 7, n. 1, p. 25–45, 2010. Cited 2 times in pages 33 and 35.

SCANLAN, M.; FILION, Y. R. Application of energy use indicators to evaluate energy dynamics in canadian water distribution systems. In: *13th International Conference on Computing and Control for the Water Industry CCWI2015*. [S.l.]: Elsevier, 2015. v. 119, p. 1039–1048. Cited in page 28.

SCHWALLER, J.; ZYL, J. E. van. Modeling the pressure leakage response of water distribution systems based on idividual leak behavior. *Journal of Hydraulics Engineering*, ASCE, v. 141, n. 04014089, p. 1–8, 2015. Cited 6 times in pages 35, 36, 37, 42, 43, and 44.

THORNTON, J.; STURM, R.; KUNEL, G. *Water Loss Control*. 2. ed. [S.l.]: Mc Graw Hill, 2008. Cited 5 times in pages 31, 32, 34, 36, and 43.

WALSKI, T. et al. Understanding the hydraulics of water distribution sysetm leaks. In: *World Water and Environmental Resources Congress 2004*. [S.l.]: ASCE, 2004. p. 1–10. Cited 2 times in pages 45 and 85.

WALSKI, T. et al. Pressure vs. flow relationship for pipe leaks. In: *World Environmental and Water Resources Congress*. [S.l.: s.n.], 2009. p. 1–10. Cited 8 times in pages 29, 36, 37, 43, 44, 52, 78, and 83.

WRIGHT, R.; STOIANOV, I.; PARPAS, P. Dynamic topology in water distribution networks. In: *12th International Conference on Computing and Control for the Water Industry CCWI2013*. [S.l.]: Elsevier, 2014. v. 70, p. 1735–1744. Cited in page 36.

XU, Q. et al. Water saving and energy reduction through pressure management in urban water distribution networks. *Water Resources Manage*, Springer, v. 28, n. 11, p. 3715–3726, 2014. Cited 2 times in pages 28 and 32.

XU, Q. et al. Review on water leakage control in distribution networks and associated environmental benefits. *Journal of Environmental Sciences*, Elsevier, v. 26, n. 5, p. 955–961, 2014. Cited in page 36.

ZYL, J. E. van. The effect of pressure on leaks in water distribution systems. In: *Water Institute of Southern Africa (WISA) Biennial Conference*. [S.l.: s.n.], 2004. p. 1104–1109. Cited 2 times in pages 32 and 33.

ZYL, J. E. van. Theoretical modeling of pressure and leakage in water distribution systems. In: *16th Conference on Water Distribution Systems Analysis, WDSA 2014*. [S.l.]: Elsevier, 2014. v. 89, p. 273–277. Cited 5 times in pages 29, 36, 41, 43, and 44.

ZYL, J. E. van; CASSA, A. M. Modeling elastically deforming leaks in water distribution pipes. *Journal of Hydraulics Engineering*, ASCE, v. 140, p. 182–189, 2014. Cited 3 times in pages 43, 44, and 66.

ZYL, J. E. van; CLAYTON, C. R. I. The effect of pressure on leakage in water distribution systems. *Proceedings of the ICE-Water Management*, Thomas Telford, v. 160, n. 2, p. 109–114, 2007. Cited 4 times in pages 37, 42, 43, and 44.

Annex

Annex I - Experimental Data

The experimental data collected in the leakage experiments is presented at Table 13, according to the columns description below. For the present data analysis were assumed a constant water density $\rho = 1000\,kg/m^3$ and a gravity acceleration $g = 9.787604\,m/s^2$.

$\boldsymbol{G}$: Test group in Table 12, regarding the orifice diameter, pipe material and pipe diameter.

Table 12 – Test Groups

Orifice (mm)	PVC 1"	PVC 3"	Steel 1"	Steel 3"
No Leak	1	2	3	4
1.5	5	6	7	8
2.5	9	10	11	12
5.0	13	14	15	16
10.0	17	18	19	20

$\boldsymbol{Pump}$: Percentage hydraulic pumps capacity adopted by the frequency inverters configuration.

$\boldsymbol{t}$: Total collection period of the leakage flow into the stocking recipient.

$\boldsymbol{M}$: Mass of measurement reservoir.

$\boldsymbol{h_{ext}}$: Measurement of the external pressure head over the orifice.

$\boldsymbol{\delta h_{ext}}$: Error in the measurement of the external pressure head over the orifice.

$\boldsymbol{h_{leak}}$: Estimation of the system pressure head in the leakage point, developed by the analysis of four pressure sensors in the leak neighborhood.

$\boldsymbol{\delta h_{leak}}$: Error of the system pressure head in the leakage point.

$\boldsymbol{h_0}$: Measurement of the system initial pressure head, next to the hydraulic pumps exit.

$\boldsymbol{\delta h_0}$: Error of the system initial pressure head.

$\boldsymbol{Q}$: Estimation of the system pumped flow, developed by the analysis of four electromagnetic flow sensors.

$\boldsymbol{\delta Q}$: Error in system pumped flow estimations.

$\boldsymbol{E_{elec}}$: Measurement of the total electrical power consumption by the hydraulic pumps.

$\boldsymbol{\delta E_{elec}}$: Error in the total electrical power consumption.

Table 13 – Experimental Data

$\boldsymbol{G}$	$\boldsymbol{Pump}$ (%)	$\boldsymbol{T}$ $(\boldsymbol{s})$	$\boldsymbol{M}$ $(\boldsymbol{kg})$	$\boldsymbol{h_{ext}}$ $(\boldsymbol{m})$	$\boldsymbol{\delta h_{ext}}$ $(\boldsymbol{m})$	$\boldsymbol{h_{leak}}$ $(\boldsymbol{m})$	$\boldsymbol{\delta h_{leak}}$ $(\boldsymbol{m})$	$\boldsymbol{h_0}$ $(\boldsymbol{m})$	$\boldsymbol{\delta h_0}$ $(\boldsymbol{m})$	$\boldsymbol{Q}$ $(\boldsymbol{m^3/s})$	$\boldsymbol{\delta Q}$ $(\boldsymbol{m^3/s})$	$\boldsymbol{E_{elec}}$ $(\boldsymbol{W})$	$\boldsymbol{\delta E_{elec}}$ $(\boldsymbol{W})$
1	23	300				5.27	0.06	5.84	0.03	7.99E-05	1.29E-05	576	1.68E+00
1	23	300				6.22	0.07	6.97	0.04	1.06E-04	1.86E-05	636	1.28E+00
1	30	300				10.39	0.06	10.99	0.04	1.80E-04	1.06E-05	949	2.48E+00
1	30	300				10.34	0.07	10.95	0.04	1.87E-04	4.40E-06	925	1.62E+00
1	38	300				15.70	0.08	16.50	0.06	2.49E-04	9.96E-06	1374	4.70E+00
1	38	300				15.60	0.08	16.42	0.07	2.56E-04	6.93E-06	1348	3.20E+00
1	44	300				20.76	0.29	21.75	0.22	3.06E-04	2.78E-05	1644	1.03E+01
1	44	300				20.66	0.09	21.65	0.09	3.10E-04	7.23E-06	1611	5.12E+00
1	49	300				25.50	0.17	26.64	0.11	3.50E-04	1.15E-05	2089	5.29E+00
1	49	300				25.36	0.13	26.50	0.11	3.60E-04	3.84E-06	2056	4.41E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
1	66	300				30.40	0.14	31.64	0.19	3.93E-04	2.52E-06	2286	9.52E+00
1	66	300				30.27	0.14	31.62	0.18	4.08E-04	4.48E-06	2253	7.51E+00
1	70	300				35.31	0.18	36.74	0.25	4.40E-04	2.43E-06	2470	6.82E+00
1	70	300				35.20	0.19	36.70	0.26	4.53E-04	2.58E-06	2439	7.63E+00
1	75	300				40.48	0.20	42.10	0.30	4.82E-04	2.60E-06	2767	7.51E+00
1	75	300				40.37	0.21	42.05	0.28	5.00E-04	2.81E-06	2747	5.35E+00
1	79	300				45.06	0.23	46.83	0.38	5.27E-04	1.17E-05	2929	1.35E+01
1	79	300				44.92	0.26	46.79	0.35	5.42E-04	3.06E-06	2877	7.33E+00
1	88	300				55.34	0.41	57.60	0.50	6.21E-04	7.69E-06	3295	6.38E+00
1	88	300				55.13	0.37	57.43	0.47	6.40E-04	4.26E-06	3246	4.48E+00
1	93	300				59.89	0.42	62.38	0.52	6.67E-04	3.04E-06	3725	3.89E+00
1	93	300				59.68	0.41	62.29	0.57	6.83E-04	3.00E-06	3675	6.43E+00
1	100	300				70.22	0.50	73.21	0.73	7.58E-04	1.74E-05	4517	1.17E+01
1	100	300				70.03	0.55	73.14	0.70	7.69E-04	3.21E-06	4456	5.27E+00
2	23	300				6.23	0.06	6.94	0.06	1.19E-04	2.51E-06	659	1.59E+00
2	24	300				10.85	0.07	11.43	0.14	1.97E-04	3.03E-06	764	4.51E+00
2	29	300				15.21	0.10	16.13	0.21	2.56E-04	2.92E-06	949	1.28E+01
2	54	300				20.21	0.09	21.31	0.19	3.13E-04	2.75E-06	1650	4.98E+00
2	59	180				25.25	0.11	26.57	0.19	3.67E-04	2.60E-06	1882	4.35E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
2	65	180				30.16	0.14	31.64	0.25	4.28E-04	2.78E-06	2124	3.66E+00
2	70	180				35.00	0.16	36.71	0.32	4.58E-04	2.75E-06	2448	4.36E+00
2	75	180				40.23	0.17	42.05	0.30	5.03E-04	2.65E-06	2771	2.78E+00
2	80	180				45.65	0.20	47.68	0.28	5.49E-04	2.52E-06	2941	5.79E+00
2	86	180				51.05	0.23	53.27	0.37	5.94E-04	2.55E-06	3356	2.84E+00
3	23	300				6.21	0.06	7.02	0.05	1.13E-04	2.40E-06	648	1.42E+00
3	30	300				10.34	0.08	11.01	0.07	1.81E-04	3.47E-06	941	3.29E+00
3	38	300				15.64	0.12	16.50	0.10	2.49E-04	4.12E-06	1369	3.18E+00
3	44	300				20.70	0.14	21.74	0.15	3.02E-04	1.52E-05	1632	4.36E+00
3	49	300				25.41	0.15	26.63	0.18	3.51E-04	3.70E-06	2080	4.68E+00
3	66	300				30.37	0.18	31.72	0.26	3.98E-04	2.85E-06	2285	9.97E+00
3	70	300				35.25	0.24	36.80	0.33	4.47E-04	2.61E-06	2463	6.22E+00
3	75	300				40.45	0.28	42.11	0.36	4.94E-04	2.80E-06	2760	5.64E+00
3	79	300				44.98	0.35	46.89	0.45	5.38E-04	3.07E-06	2869	4.88E+00
3	84	300				50.21	0.40	52.29	0.46	5.61E-04	5.14E-06	3013	4.35E+00
3	88	300				55.18	0.45	57.59	0.53	6.29E-04	2.58E-06	3242	4.22E+00
3	100	300				70.16	0.60	73.19	0.67	7.58E-04	2.68E-06	4484	6.31E+00
4	23	300				6.36	0.06	6.97	0.04	1.27E-04	5.66E-06	643	1.49E+00
4	30	300				10.48	0.06	10.95	0.05	1.88E-04	3.29E-06	937	2.54E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
4	38	300				15.58	0.06	16.41	0.08	2.42E-04	3.29E-06	1350	4.69E+00
4	44	300				20.64	0.06	21.58	0.11	2.86E-04	2.26E-06	1600	3.39E+00
4	49	300				24.80	0.19	25.87	0.20	3.25E-04	2.57E-06	2054	3.45E+00
4	66	300				30.45	0.08	31.68	0.20	3.72E-04	2.53E-06	2243	8.26E+00
4	70	300				35.40	0.16	36.81	0.24	4.15E-04	8.75E-06	2424	5.76E+00
4	75	300				40.56	0.16	42.12	0.26	4.63E-04	2.34E-06	2698	6.01E+00
4	79	300				45.19	0.17	46.90	0.29	5.03E-04	2.57E-06	2801	1.75E+01
4	84	300				50.36	0.21	52.31	0.35	5.53E-04	3.10E-06	2941	5.68E+00
4	88	240				55.46	0.23	57.58	0.40	5.97E-04	3.53E-06	3213	3.73E+00
4	100	300				70.50	0.32	73.28	0.72	7.22E-04	2.96E-06	4468	6.50E+00
5	23	600	8.2	0.75	0.000	5.99	0.07	6.74	0.06	1.31E-04	9.97E-06	625	1.66E+00
5	23	600	8.3	0.75	0.000	5.99	0.07			1.34E-04	2.77E-06	617	1.89E+00
5	23	780	10.8	0.75	0.000	6.00	0.08	6.78	0.06	1.42E-04	5.61E-06	618	1.38E+00
5	32	600	12.3	0.75	0.000	11.18	0.07	11.87	0.08	2.10E-04	2.79E-06	990	1.62E+00
5	32	600	12.3	0.75	0.000	11.03	0.07	11.78	0.08	2.27E-04	3.09E-06	966	1.83E+00
5	32	660	13.4	0.75	0.000	11.03	0.07	11.79	0.07	2.37E-04	2.93E-06	972	2.44E+00
5	38	600	15.2	0.75	0.000	15.87	0.08	16.75	0.11	2.73E-04	3.25E-06	1359	3.64E+00
5	38	600	15.2	0.75	0.000	15.78	0.10	16.70	0.09	2.90E-04	2.65E-06	1335	2.33E+00
5	38	600	15.2	0.75	0.000	15.73	0.09	16.67	0.16	3.04E-04	2.69E-06	1344	2.59E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
5	44	600	17.5	0.75	0.000	20.82	0.14	21.94	0.11	3.47E-04	2.69E-06	1609	2.46E+00
5	44	600	17.5	0.75	0.000	20.83	0.17	21.97	0.15	3.56E-04	2.63E-06	1625	3.10E+00
5	44	600	17.5	0.75	0.000	20.74	0.11	21.90	0.13	3.67E-04	2.52E-06	1613	2.36E+00
5	49	600	18.9	0.75	0.000	25.52	0.11	26.87	0.13	4.11E-04	3.77E-06	2100	5.38E+00
5	49	600	18.7	0.75	0.000	25.48	0.11	26.83	0.14	4.12E-04	2.98E-06	2088	2.12E+00
5	49	600	18.8	0.75	0.000	25.41	0.17	26.75	0.19	4.21E-04	2.62E-06	2093	1.97E+00
5	67	600	20.3	0.75	0.000	30.41	0.18	31.89	0.26	4.52E-04	2.77E-06	2247	4.37E+00
5	67	600	20.1	0.75	0.000	30.35	0.17	31.86	0.26	4.53E-04	2.59E-06	2236	4.59E+00
5	67	600	20.3	0.75	0.000	30.53	0.17	32.03	0.25	4.59E-04	6.29E-05	2332	1.22E+01
5	72	600	21.5	0.75	0.000	35.53	0.21	37.20	0.31	5.03E-04	2.81E-06	2498	1.15E+01
5	72	660	23.7	0.75	0.000	35.61	0.21	37.33	0.30	5.05E-04	2.59E-06	2549	1.85E+01
5	72	600	21.4	0.75	0.000	35.44	0.21	37.17	0.29	5.16E-04	2.90E-06	2508	5.16E+00
5	77	600	22.7	0.75	0.000	40.65	0.25	42.51	0.34	5.46E-04	2.82E-06	2753	4.76E+00
5	77	600	22.5	0.75	0.000	40.59	0.26	42.46	0.34	5.50E-04	2.71E-06	2742	4.21E+00
5	77	600	22.7	0.75	0.000	40.64	0.25	42.55	0.36	5.52E-04	2.88E-06	2773	6.85E+00
5	82	600	23.8	0.75	0.000	45.58	0.34	47.73	0.42	5.71E-04	2.73E-05	3055	4.66E+00
5	82	600	23.6	0.75	0.000	45.56	0.36	47.68	0.42	5.95E-04	3.32E-06	3037	6.15E+00
5	82	600	23.7	0.75	0.000	45.59	0.42	47.74	0.46	6.04E-04	2.81E-06	3062	4.32E+00
5	86	600	24.7	0.75	0.000	50.24	0.43	52.53	0.45	5.94E-04	1.08E-05	3226	5.46E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
5	86	600	24.8	0.75	0.000	50.46	0.52	52.75	0.59	6.35E-04	3.87E-06	3298	1.61E+01
5	86	600	24.7	0.75	0.000	50.35	0.35	52.66	0.44	6.37E-04	3.48E-06	3252	5.42E+00
5	90	600	25.7	0.75	0.000	54.45	0.37	57.11	0.43	7.02E-04	2.90E-06	3749	1.15E+01
6	23	900	15.1	0.78	0.000	5.56	0.07	6.76	0.06	1.34E-04	3.34E-06	635	1.55E+00
6	23	900	15.0	0.78	0.000	5.47	0.07	6.67	0.05	1.35E-04	3.37E-06	631	1.75E+00
6	23	900	15.0	0.78	0.000	5.53	0.07	6.73	0.06	1.36E-04	5.69E-05	629	2.01E+00
6	31	600	18.6	0.78	0.000	15.28	0.22	16.60	0.26	2.50E-04	3.41E-06	1000	2.94E+00
6	32	600	15.5	0.78	0.000	10.57	0.06	11.73	0.06	2.02E-04	2.85E-06	999	1.17E+00
6	32	600	15.9	0.78	0.000	10.88	0.06	12.07	0.06	2.07E-04	2.64E-06	1027	2.96E+00
6	32	600	15.8	0.78	0.000	10.84	0.08	12.04	0.08	2.10E-04	3.31E-06	1020	1.82E+00
6	39	600	18.5	0.78	0.000	14.99	0.18	16.31	0.20	2.49E-04	3.17E-06	1435	7.28E+00
6	39	600	18.6	0.78	0.000	15.64	0.25	16.99	0.26	2.57E-04	7.89E-06	1421	4.39E+00
6	49	600	21.7	0.78	0.000	24.24	0.32	25.74	0.36	3.30E-04	3.66E-06	1905	4.11E+00
6	55	600	20.4	0.78	0.000	20.28	0.50	21.72	0.53	3.00E-04	5.06E-06	1653	1.11E+01
6	55	600	20.0	0.78	0.000	19.03	0.79	20.47	0.83	2.81E-04	7.85E-06	1691	3.51E+00
6	55	600	20.4	0.78	0.000	20.34	0.56	21.78	0.58	2.95E-04	6.52E-06	1659	1.07E+01
6	60	600	22.2	0.78	0.000	25.72	0.08	27.25	0.21	3.36E-04	2.72E-06	1961	1.25E+01
6	61	600	21.8	0.78	0.000	24.19	0.77	25.80	0.80	3.47E-04	8.80E-06	1945	3.84E+00
6	66	600	23.5	0.78	0.000	30.99	0.09	32.56	0.29	3.64E-04	3.52E-06	2261	9.95E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
6	68	600	23.5	0.78	0.000	30.88	0.08	32.52	0.25	3.79E-04	2.72E-06	2251	9.07E+00
6	68	600	23.5	0.78	0.000	30.14	0.11	31.75	0.20	3.87E-04	2.75E-06	2304	3.81E+00
6	71	600	25.1	0.78	0.000	35.78	0.13	37.47	0.27	4.32E-04	2.94E-06	2521	4.97E+00
6	72	600	25.2	0.78	0.000	36.16	0.09	37.84	0.23	4.22E-04	1.29E-05	2566	7.75E+00
6	73	600	25.0	0.78	0.000	35.75	0.09	37.48	0.29	4.21E-04	2.68E-06	2538	6.60E+00
6	77	600	26.4	0.78	0.000	40.62	0.10	42.20	0.30	4.43E-04	2.98E-06	2764	4.72E+00
6	78	600	26.5	0.78	0.000	41.32	0.09	43.10	0.31	4.64E-04	2.70E-06	2846	4.21E+00
6	78	600	26.3	0.78	0.000	40.59	0.11			4.61E-04	2.75E-06	2864	8.54E+00
6	81	600	27.7	0.78	0.000	45.72	0.11	47.43	0.31	4.77E-04	2.95E-06	3083	9.18E+00
6	82	600	27.7	0.78	0.000	46.06	0.11	47.83	0.31	4.95E-04	3.24E-06	3109	4.71E+00
6	83	600	27.9	0.78	0.000	46.62	0.20	48.48	0.33	4.99E-04	2.99E-06	3188	4.71E+00
6	86	600	28.9	0.78	0.000	50.98	0.12	52.83	0.33	5.30E-04	4.20E-06	3337	7.13E+00
6	86	600	28.9	0.78	0.000	50.87	0.13	52.82	0.33	5.48E-04	4.50E-06	3367	2.32E+01
6	89	600	28.9	0.78	0.000	50.95	0.11	52.77	0.37	5.26E-04	3.24E-06	3288	3.76E+00
7	23	900	12.3	0.75	0.000	5.97	0.07	6.76	0.07	1.36E-04	9.02E-06	622	1.56E+00
7	23	780	10.7	0.75	0.000	6.01	0.07	6.81	0.07	1.39E-04	3.64E-06	625	1.77E+00
7	23	900	12.3	0.75	0.000	6.02	0.13	6.84	0.06	1.42E-04	2.94E-06	620	1.57E+00
7	32	600	12.2	0.75	0.000	11.11	0.07	11.87	0.06	2.28E-04	6.11E-06	986	1.83E+00
7	32	600	12.3	0.75	0.000	11.13	0.08	11.80	0.09	2.30E-04	2.71E-06	975	1.39E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
7	32	600	12.3	0.75	0.000	11.03	0.08	11.79	0.10	2.32E-04	2.74E-06	975	2.07E+00
7	38	600	14.2	0.75	0.000	15.81	0.10	16.71	0.14	2.86E-04	2.62E-06	1380	3.82E+00
7	38	660	15.6	0.75	0.000	15.80	0.16	16.76	0.11	2.92E-04	2.71E-06	1355	2.51E+00
7	38	600	14.2	0.75	0.000	15.73	0.08	16.68	0.11	2.94E-04	2.74E-06	1342	2.11E+00
7	44	600	15.5	0.75	0.000	20.83	0.12	21.98	0.20	3.51E-04	2.62E-06	1631	3.10E+00
7	44	600	15.6	0.75	0.000	20.81	0.12	21.96	0.14	3.55E-04	2.64E-06	1616	2.20E+00
7	44	600	15.6	0.75	0.000	20.79	0.12	21.97	0.17	3.56E-04	3.53E-06	1641	3.25E+00
7	49	600	16.7	0.75	0.000	25.54	0.15	26.89	0.15	4.06E-04	2.78E-06	2090	2.62E+00
7	49	600	16.8	0.75	0.000	25.52	0.13	26.90	0.17	4.12E-04	2.92E-06	2114	3.22E+00
7	49	600	16.8	0.75	0.000	25.53	0.13	26.92	0.15	4.15E-04	7.06E-06	2110	6.08E+00
7	67	600	17.9	0.75	0.000	30.35	0.19	31.92	0.27	4.56E-04	2.68E-06	2256	3.38E+00
7	67	600	17.9	0.75	0.000	30.38	0.21	31.92	0.28	4.59E-04	2.80E-06	2248	3.55E+00
7	67	600	18.1	0.75	0.000	30.78	0.17	32.37	0.24	4.68E-04	3.04E-06	2301	4.68E+00
7	72	600	19.0	0.75	0.000	35.54	0.22	37.32	0.31	5.09E-04	2.77E-06	2538	1.35E+01
7	72	600	19.1	0.75	0.000	35.52	0.22	37.26	0.31	5.12E-04	2.56E-06	2521	5.25E+00
7	72	600	19.8	0.75	0.000	38.99	0.30	40.83	0.42	5.34E-04	2.68E-06	2449	4.34E+00
7	77	600	20.1	0.75	0.000	40.65	0.26	42.55	0.35	5.48E-04	2.69E-06	2761	5.04E+00
7	77	600	20.1	0.75	0.000	40.60	0.26	42.55	0.32	5.51E-04	2.67E-06	2779	4.51E+00
7	77	600	20.1	0.75	0.000	40.59	0.28	42.54	0.38	5.53E-04	2.90E-06	2761	4.33E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
7	82	600	21.1	0.75	0.000	45.76	0.32	47.88	0.41	5.90E-04	2.62E-06	3115	1.02E+01
7	82	600	21.1	0.75	0.000	45.66	0.31	47.77	0.44	5.93E-04	3.09E-06	3076	4.10E+00
7	82	600	21.0	0.75	0.000	45.59	0.35	47.71	0.42	5.93E-04	2.71E-06	3062	6.71E+00
7	86	600	21.8	0.75	0.000	50.47	0.36	52.76	0.45	6.29E-04	2.89E-06	3288	9.98E+00
7	86	600	22.0	0.75	0.000	50.56	0.40	52.85	0.57	6.40E-04	5.95E-05	3320	2.12E+01
7	86	600	22.1	0.75	0.000	50.76	0.42	53.14	0.53	6.39E-04	9.25E-06	3312	7.46E+00
8	23	1020	14.7	0.78	0.000	5.99	0.07	6.66	0.08	1.32E-04	1.60E-05	619	1.51E+00
8	23	900	13.0	0.78	0.000	5.99	0.08	6.67	0.06	1.35E-04	9.04E-06	620	1.59E+00
8	23	720	10.4	0.78	0.000	6.16	0.07	6.84	0.05	1.35E-04	1.28E-05	631	1.95E+00
8	32	600	13.0	0.78	0.000	11.13	0.07	11.75	0.08	2.24E-04	1.63E-05	976	2.40E+00
8	32	600	13.2	0.78	0.000	11.06	0.07	11.69	0.11	2.28E-04	1.93E-05	973	1.94E+00
8	32	600	13.1	0.78	0.000	11.01	0.07	11.61	0.10	2.33E-04	1.34E-05	1001	2.20E+00
8	35	660	18.7	0.78	0.000	20.32	0.35	21.48	0.41	3.47E-04	1.85E-05	1207	4.07E+00
8	39	600	15.6	0.78	0.000	16.02	0.08	17.03	0.13	3.05E-04	1.57E-05	1366	1.97E+00
8	39	600	15.8	0.78	0.000	16.53	0.08	17.52	0.09	3.03E-04	1.66E-05	1404	2.90E+00
8	40	600	15.5	0.78	0.000	15.63	0.08	16.59	0.12	3.00E-04	1.52E-05	1418	3.48E+00
8	46	600	17.5	0.78	0.000	21.53	0.13	22.77	0.19	3.73E-04	1.76E-05	1791	2.63E+00
8	49	600	18.4	0.78	0.000	25.93	0.08	27.33	0.17	4.07E-04	1.75E-05	2187	6.04E+00
8	49	600	18.7	0.78	0.000	26.20	0.12	27.70	0.22	4.36E-04	1.83E-05	1912	3.28E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
8	55	600	17.0	0.78	0.000	21.00	0.10	22.19	0.16	3.56E-04	1.68E-05	1687	3.60E+00
8	55	600	17.0	0.78	0.000	21.06	0.09	22.14	0.16	3.59E-04	1.64E-05	1667	3.08E+00
8	61	600	18.6	0.78	0.000	26.18	0.13	27.64	0.18	4.31E-04	2.25E-05	1904	3.15E+00
8	67	600	20.0	0.78	0.000	30.95	0.14	32.63	0.19	4.74E-04	1.89E-05	2303	3.33E+00
8	68	720	23.9	0.78	0.000	30.94	0.13	32.62	0.20	4.79E-04	1.89E-05	2308	4.47E+00
8	70	720	24.0	0.78	0.000	30.92	0.08	32.53	0.21	4.54E-04	1.91E-05	2402	6.22E+00
8	72	600	20.9	0.78	0.000	35.98	0.17	37.81	0.27	5.04E-04	1.96E-05	2544	6.25E+00
8	73	600	20.9	0.78	0.000	35.98	0.16	37.85	0.22	5.01E-04	1.96E-05	2616	1.89E+01
8	75	600	21.1	0.78	0.000	35.80	0.09	37.58	0.25	4.97E-04	1.99E-05	2642	4.65E+00
8	77	600	22.3	0.78	0.000	40.85	0.20	42.89	0.23	5.61E-04	2.09E-05	2785	4.20E+00
8	78	660	24.2	0.78	0.000	41.06	0.18	43.09	0.27	5.47E-04	2.57E-05	2855	9.25E+00
8	80	600	22.3	0.78	0.000	40.49	0.13	42.45	0.29	5.39E-04	2.10E-05	2941	6.38E+00
8	83	600	23.3	0.78	0.000	45.83	0.22	48.08	0.27	6.06E-04	2.18E-05	3085	3.60E+00
8	83	600	23.4	0.78	0.000	46.08	0.21	48.31	0.25	6.04E-04	2.20E-05	3297	5.44E+00
8	85	600	23.3	0.78	0.000	45.79	0.13			5.86E-04	2.77E-05	3534	4.11E+00
8	86	600	24.5	0.78	0.000	51.16	0.25	53.60	0.32	6.47E-04	2.31E-05	3337	1.12E+01
8	86	600	24.4	0.78	0.000	50.67	0.23			6.50E-04	2.27E-05	3302	1.35E+01
8	89	600	24.4	0.78	0.000	51.34	0.15	53.76	0.37	6.37E-04	2.35E-05	3633	5.42E+00
9	30	600	38.8	0.59	0.000	9.02	0.02					902	4.09E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
9	30	600	38.5	0.59	0.000	8.91	0.02					915	7.02E-01
9	35	600	45.6	0.59	0.002	12.17	0.02					1196	1.76E+00
9	35	600	45.5	0.59	0.000	12.25	0.03					1167	1.07E+00
9	35	600	45.2	0.59	0.000	12.06	0.02					1190	1.23E+00
9	50	600	53.3	0.59	0.001	16.95	0.04					1473	5.05E+00
9	50	600	53.3	0.59	0.001	16.80	0.04					1470	4.10E+00
9	50	600	53.3	0.59	0.002	16.96	0.04					1475	2.34E+00
9	55	600	57.3	0.59	0.001	20.54	0.05					1698	3.74E+00
9	55	600	57.0	0.59	0.001	20.40	0.05					1702	2.82E+00
9	60	600	60.7	0.59	0.002	24.40	0.07					1938	5.79E+00
9	60	600	60.7	0.59	0.002	24.51	0.08					1883	2.07E+00
9	70	600	68.5	0.59	0.002	33.38	0.11					2454	3.57E+00
9	70	600	68.2	0.59	0.003	33.24	0.11					2526	3.64E+00
9	70	600	68.1	0.59	0.002	33.06	0.08					2484	5.00E+00
9	80	600	76.2	0.59	0.003	43.54	0.11					2991	2.37E+01
9	80	600	76.0	0.59	0.003	43.54	0.17					2817	2.82E+00
9	80	600	75.9	0.59	0.003	43.18	0.11					2934	1.19E+01
9	90	600	82.2	0.59	0.003	52.35	0.17					3872	6.90E+01

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
9	90	600	82.1	0.59	0.002	52.11	0.12					3865	4.39E+00
9	95	600	87.0	0.59	0.005	59.57	0.23					4197	2.83E+01
9	95	600	86.7	0.59	0.004	59.49	0.20					4208	1.47E+01
9	95	600	86.6	0.59	0.003	59.11	0.16					4181	1.64E+01
10	23	600	27.4	0.78	0.000	5.47	0.17	6.68	0.06	1.69E-04	3.28E-06	620	1.14E+00
10	23	600	27.2	0.78	0.000	5.39	0.07	6.63	0.07	1.73E-04	3.49E-06	629	2.49E+00
10	23	600	26.9	0.78	0.000	5.39	0.07	6.62	0.07	1.74E-04	2.99E-06	635	3.50E+00
10	32	600	42.9	0.78	0.000	11.05	0.07	12.34	0.11	2.60E-04	2.79E-06	1033	1.17E+00
10	33	600	43.0	0.78	0.000	11.01	0.07	12.35	0.10	2.63E-04	3.24E-06	1059	3.39E+00
10	33	780	55.8	0.78	0.000	10.99	0.07	12.31	0.10	2.72E-04	2.77E-06	1046	1.57E+00
10	39	600	53.3	0.78	0.000	15.83	0.07	17.35	0.10	3.28E-04	2.72E-06	1396	3.13E+00
10	39	600	53.3	0.78	0.000	15.74	0.07	17.30	0.09	3.38E-04	2.70E-06	1411	2.08E+00
10	55	600	58.3	0.78	0.000	20.13	0.45	21.79	0.49	3.76E-04	5.13E-06	1706	4.80E+00
10	55	600	58.7	0.78	0.000	20.42	0.11	22.11	0.13	3.88E-04	2.78E-06	1697	4.78E+00
10	56	600	57.7	0.78	0.000	19.49	0.42	21.15	0.45	3.73E-04	5.39E-06	1737	7.12E+00
10	61	600	64.6	0.78	0.001	25.58	0.15	27.43	0.24	4.34E-04	2.98E-06	2122	3.41E+00
10	61	600	63.8	0.78	0.001	25.85	0.12	27.72	0.16	4.44E-04	2.81E-06	1957	3.19E+00
10	61	600	63.7	0.78	0.001	25.80	0.09	27.70	0.20	4.54E-04	3.04E-06	1945	3.20E+00
10	67	600	68.5	0.78	0.001	30.86	0.08	32.84	0.22	4.74E-04	2.95E-06	2280	7.67E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
10	67	600	67.9	0.78	0.001	30.68	0.11	32.70	0.24	4.97E-04	2.97E-06	2243	2.98E+00
10	68	600	69.4	0.78	0.001	30.72	0.20	32.95	0.28	4.92E-04	2.94E-06	2449	3.10E+00
10	71	600	72.2	0.78	0.002	35.66	0.09	37.83	0.25	5.17E-04	6.97E-06	2562	4.22E+00
10	72	600	72.4	0.78	0.002	36.02	0.15	38.16	0.26	5.42E-04	2.94E-06	2581	2.88E+00
10	73	600	72.2	0.78	0.002	35.48	0.09	37.58	0.28	5.14E-04	3.17E-06	2600	1.53E+01
10	77	600	76.5	0.78	0.002	41.07	0.08	43.21	0.30	5.62E-04	3.61E-06	2836	7.57E+00
10	77	600	76.1	0.78	0.002	40.90	0.17	43.12	0.28	5.82E-04	2.87E-06	2829	5.14E+00
10	78	600	77.1	0.78	0.002	40.36	0.10	42.56	0.28	5.68E-04	3.06E-06	2831	5.46E+00
10	81	600	81.1	0.78	0.002	45.86	0.10	48.14	0.33	6.02E-04	2.96E-06	2972	1.75E+01
10	81	600	79.9	0.78	0.002	45.65	0.10	47.92	0.35	6.05E-04	3.28E-06	2894	6.96E+00
10	86	600	79.8	0.78	0.002	45.73	0.11	47.94	0.33	5.99E-04	3.15E-06	2921	3.95E+00
10	86	600	83.3	0.78	0.002	50.63	0.11	53.11	0.33	6.56E-04	3.75E-06	3345	3.92E+00
10	87	600	85.0	0.78	0.002	51.20	0.10	53.67	0.37	6.51E-04	4.05E-06	3393	5.66E+00
10	87	600	83.2	0.78	0.002	50.69	0.14	53.13	0.35	6.56E-04	5.97E-06	3358	7.57E+00
11	23	600	23.6	0.75	0.001	6.08	0.07	6.87	0.06	1.52E-04	4.48E-06	624	1.57E+00
11	23	600	23.4	0.75	0.001	5.93	0.07	6.72	0.07	1.60E-04	3.00E-06	618	2.03E+00
11	23	600	23.1	0.75	0.001	5.93	0.07	6.79	0.06	1.61E-04	2.76E-06	619	1.58E+00
11	32	600	35.1	0.75	0.001	11.01	0.08	11.79	0.10	2.52E-04	3.15E-06	984	1.77E+00
11	32	600	33.8	0.75	0.001	10.92	0.09	11.79	0.08	2.60E-04	4.82E-06	975	1.86E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
11	32	600	34.8	0.75	0.001	10.90	0.08	11.73	0.10	2.63E-04	3.09E-06	972	1.93E+00
11	38	600	40.8	0.75	0.001	15.99	0.12	17.08	0.11	3.34E-04	2.77E-06	1361	2.27E+00
11	38	600	40.6	0.75	0.001	15.96	0.28	17.06	0.11	3.36E-04	2.83E-06	1364	2.14E+00
11	39	600	41.0	0.75	0.001	15.98	0.08	17.06	0.11	3.35E-04	2.87E-06	1376	2.02E+00
11	44	600	45.1	0.75	0.001	20.98	0.12	22.29	0.15	3.95E-04	2.93E-06	1657	2.28E+00
11	44	600	44.9	0.75	0.001	20.56	0.12	21.86	0.15	3.97E-04	3.50E-06	1624	5.65E+00
11	45	660	49.8	0.75	0.001	21.00	0.10	22.29	0.15	3.92E-04	2.99E-06	1656	2.22E+00
11	49	600	48.7	0.75	0.001	25.68	0.14	27.22	0.18	4.51E-04	2.80E-06	2159	2.19E+00
11	50	600	48.9	0.75	0.001	25.75	0.14	27.25	0.22	4.49E-04	2.80E-06	2158	2.52E+00
11	50	660	54.5	0.75	0.001	26.44	0.20			4.48E-04	3.00E-06	2313	1.65E+01
11	67	600	52.4	0.75	0.001	30.79	0.22	32.42	0.29	4.87E-04	2.98E-06	2353	1.02E+01
11	67	480	41.7	0.75	0.001	30.54	0.18	32.30	0.26	5.02E-04	2.92E-06	2295	4.64E+00
11	68	600	52.6	0.75	0.001	30.94	0.20	32.68	0.28	5.02E-04	2.88E-06	2315	3.08E+00
11	72	600	55.6	0.75	0.002	35.57	0.22	37.58	0.31	5.59E-04	2.87E-06	2514	2.89E+00
11	73	600	55.8	0.75	0.002	35.70	0.22	37.67	0.30	5.51E-04	2.88E-06	2520	4.28E+00
11	73	600	55.7	0.75	0.002	35.60	0.22	37.60	0.32	5.58E-04	2.92E-06	2527	3.09E+00
11	77	600	59.1	0.75	0.002	40.97	0.29	43.08	0.38	5.90E-04	2.72E-06	2840	9.42E+00
11	77	600	58.9	0.75	0.002	40.79	0.26	42.93	0.35	5.98E-04	3.00E-06	2792	3.60E+00
11	78	600	58.9	0.75	0.002	40.77	0.28	42.97	0.35	6.05E-04	3.01E-06	2802	4.78E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
11	82	600	61.7	0.75	0.002	45.74	0.34	48.16	0.48	6.44E-04	2.93E-06	3108	3.79E+00
11	82	600	61.3	0.75	0.002	45.71	0.32	48.19	0.40	6.54E-04	2.75E-06	3120	6.60E+00
11	82	600	61.7	0.75	0.002	45.76	0.34	48.20	0.46	6.53E-04	3.08E-06	3126	3.31E+00
11	86	600	63.7	0.75	0.002	50.13	0.36	52.77	0.42	6.89E-04	2.88E-06	3308	2.37E+01
11	86	600	64.0	0.75	0.002	49.99	0.36	52.61	0.47	6.94E-04	4.63E-06	3294	1.35E+01
11	86	600	64.4	0.75	0.002	50.54	0.37	53.17	0.47	6.88E-04	3.43E-06	3342	9.60E+00
12	23	660	27.5	0.78	0.000	6.01	0.07	6.72	0.30	1.64E-04	2.30E-05	622	1.94E+00
12	23	600	24.9	0.78	0.000	5.95	0.07	6.67	0.06	1.64E-04	2.29E-05	623	1.32E+00
12	23	600	25	0.78	0.000	6.02	0.07	6.72	0.05	1.68E-04	1.06E-04	628	2.79E+00
12	32	660	40.8	0.78	0.000	10.94	0.07	11.65	0.09	2.64E-04	3.31E-05	987	1.39E+00
12	32	600	37	0.78	0.000	10.91	0.08	11.65	0.08	2.65E-04	4.39E-05	985	1.68E+00
12	32	600	37.2	0.78	0.000	10.94	0.07	11.65	0.08	2.66E-04	3.33E-05	989	1.40E+00
12	39	600	44.8	0.78	0.000	16.30	0.07	17.41	0.14	3.44E-04	3.93E-05	1404	2.72E+00
12	39	600	44.7	0.78	0.000	16.24	0.24	17.38	0.09	3.48E-04	3.93E-05	1405	2.94E+00
12	39	600	44.8	0.78	0.000	16.29	0.07	17.42	0.10	3.48E-04	3.94E-05	1397	1.76E+00
12	55	600	48.7	0.78	0.000	20.76	0.10	22.14	0.32	4.03E-04	4.27E-05	1678	4.76E+00
12	55	600	48.7	0.78	0.000	20.77	0.09	22.11	0.14	4.03E-04	4.28E-05	1686	4.20E+00
12	55	600	48.5	0.78	0.000	20.73	0.10	22.10	0.15	4.06E-04	4.46E-05	1687	4.81E+00
12	61	600	53.1	0.78	0.001	26.14	0.13	27.77	0.20	4.59E-04	4.65E-05	1972	5.51E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
12	61	600	53	0.78	0.001	26.05	0.11	27.68	0.18	4.64E-04	4.63E-05	1944	3.32E+00
12	61	600	53.1	0.78	0.001	26.02	0.11	27.70	0.20	4.74E-04	4.65E-05	1930	3.25E+00
12	67	600	56.5	0.78	0.001	30.84	0.15	32.68	0.21	5.07E-04	4.93E-05	2353	4.38E+00
12	68	600	56.8	0.78	0.001	31.01	0.08	32.87	0.19	5.13E-04	5.01E-05	2422	1.27E+01
12	68	600	56.5	0.78	0.001	30.73	0.12	32.61	0.20	5.21E-04	4.92E-05	2329	3.15E+00
12	72	600	60.2	0.78	0.002	36.02	0.15	38.13	0.25	5.72E-04	5.23E-05	2571	3.75E+00
12	73	600	60	0.78	0.002	35.70	0.08	37.78	0.23	5.56E-04	5.19E-05	2607	4.65E+00
12	73	600	60.1	0.78	0.002	35.63	0.14	37.73	0.25	5.63E-04	5.23E-05	2560	3.48E+00
12	77	600	63.3	0.78	0.002	40.67	0.18	42.98	0.28	6.09E-04	5.49E-05	2835	5.70E+00
12	78	600	63.3	0.78	0.002	40.77	0.09	43.07	0.27	6.03E-04	5.47E-05	2866	7.42E+00
12	78	600	63.7	0.78	0.002	40.99	0.16			6.18E-04	5.51E-05	2853	4.80E+00
12	83	600	66.7	0.78	0.002	46.18	0.11	48.71	0.30	6.54E-04	5.76E-05	3205	6.48E+00
12	83	600	66.7	0.78	0.002	46.07	0.20	48.64	0.30	6.62E-04	5.79E-05	3174	5.07E+00
12	83	600	66.7	0.78	0.002	46.12	0.24	48.66	0.29	6.60E-04	5.77E-05	3205	1.54E+01
12	86	600	69.3	0.78	0.002	50.84	0.28	53.65	0.31	7.01E-04	6.02E-05	3394	1.22E+01
12	87	600	69.5	0.78	0.002	50.83	0.17	53.62	0.29	6.98E-04	6.03E-05	3386	4.86E+00
12	87	600	69.5	0.78	0.002	50.86	0.21	53.65	0.33	7.04E-04	6.72E-05	3410	1.04E+01
13	23	600	77.8	0.64	0.001	5.82	0.07	6.39	0.05			629	1.10E+00
13	23	600	75.2	0.64	0.001	5.75	0.06			2.52E-04	2.82E-06	626	1.18E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
13	23	600	75.7	0.64	0.001	5.74	0.07	6.43	0.06	2.57E-04	3.82E-06	627	9.20E-01
13	32	600	115.7	0.65	0.001	10.86	0.08	11.76	0.05			1019	1.30E+00
13	32	600	112.6	0.65	0.002	10.69	0.08	11.79	0.06	3.85E-04	4.72E-06	1014	1.07E+00
13	32	600	110.2	0.64	0.002	10.38	0.07	11.06	0.09	4.26E-04	3.48E-06	1015	1.04E+00
13	39	540	129.1	0.65	0.002	16.03	0.09	17.21	0.09			1468	6.48E+00
13	39	540	122.5	0.65	0.003	15.17	0.07	16.35	0.10	5.35E-04	3.20E-06	1361	2.77E+00
13	46	420	117.2	0.65	0.005	21.54	0.09	23.03	0.09			1848	1.34E+00
13	46	420	114.1	0.65	0.003	21.04	0.09	23.12	0.09	6.00E-04	3.66E-06	1844	1.48E+00
13	46	420	112.8	0.65	0.002	20.76	0.09	22.55	0.09	6.29E-04	1.03E-05	1859	1.24E+01
13	61	420	126.9	0.65	0.003	25.47	0.11	27.15	0.14			1992	3.81E+00
13	61	420	128.4	0.65	0.004	26.19	0.11	27.85	0.15			2040	7.37E+00
13	61	420	123.2	0.65	0.004	24.91	0.10	27.33	0.14	7.30E-04	3.60E-06	2026	5.30E+00
13	67	360	117.7	0.65	0.006	30.51	0.11	32.41	0.22			2304	2.70E+00
13	67	360	116.1	0.65	0.003	29.90	0.11	32.52	0.18	6.83E-04	3.06E-05	2292	1.82E+00
13	68	360	116.6	0.65	0.006	30.82	0.12	33.90	0.20	8.31E-04	4.43E-06	2414	1.05E+01
13	72	360	126.0	0.65	0.006	35.69	0.12	37.82	0.19			2670	1.94E+00
13	72	360	124.5	0.65	0.004	34.93	0.13	37.96	0.21	7.56E-04	7.18E-06	2641	1.88E+00
13	74	360	125.7	0.65	0.006	36.49	0.12	40.29	0.18	9.18E-04	4.29E-06	2833	9.43E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
13	78	300	111.7	0.65	0.006	41.19	0.13	43.65	0.23			2967	5.33E+00
13	78	300	110.5	0.65	0.006	40.33	0.13	43.80	0.22	8.22E-04	4.35E-06	2906	3.21E+00
13	80	300	110.3	0.65	0.006	40.84	0.11	45.07	0.17	9.75E-04	4.36E-06	3042	1.86E+00
13	82	300	116.3	0.65	0.010	45.18	0.15					3134	7.91E+00
13	84	300	119.4	0.65	0.008	48.01	0.15	50.82	0.24			3331	8.31E+00
13	84	300	116.0	0.65	0.006	45.63	0.12	50.43	0.21	1.04E-03	4.56E-06	3290	6.81E+00
13	90	300	122.6	0.65	0.010	51.00	0.14	54.03	0.24			3687	4.12E+00
13	90	300	123.1	0.65	0.010	51.71	0.16	56.66	0.30	1.03E-03	5.03E-06	3970	2.97E+00
13	100	300	139.8	0.65	0.010	67.92	0.23	71.89	0.29			4908	1.25E+01
13	100	300	137.7	0.65	0.010	66.05	0.25	72.38	0.33	1.18E-03	5.40E-06	4870	1.32E+01
14	23	600	80.4	0.78	0.001	5.38	0.05	6.70	0.07	2.45E-04	2.98E-06	676	2.54E+00
14	23	600	81.0	0.78	0.001	5.29	0.07	6.63	0.06	2.53E-04	3.45E-06	632	1.30E+00
14	23	600	80.0	0.78	0.001	5.28	0.06	6.63	0.07	2.54E-04	2.93E-06	640	1.81E+00
14	33	600	123.6	0.78	0.002	10.51	0.06	12.18	0.08	3.86E-04	2.96E-06	1092	2.19E+00
14	33	600	125.4	0.78	0.002	10.76	0.06	12.49	0.10	4.01E-04	3.01E-06	1105	1.63E+00
14	34	600	127.1	0.78	0.002	11.05	0.07	12.80	0.09	4.06E-04	3.19E-06	1119	2.55E+00
14	40	540	137.3	0.78	0.002	15.83	0.06	17.91	0.14	4.85E-04	3.03E-06	1487	2.45E+00
14	40	540	136.9	0.78	0.002	15.70	0.07	17.82	0.12	4.93E-04	3.23E-06	1479	2.69E+00
14	41	520	133.3	0.78	0.002	16.12	0.06	18.27	0.13	5.02E-04	2.95E-06	1494	2.48E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
14	56	420	118.1	0.79	0.002	20.81	0.06	23.20	0.29	5.57E-04	3.25E-06	1867	1.01E+01
14	56	420	118.6	0.79	0.002	20.98	0.08	23.43	0.15	5.72E-04	3.65E-06	1757	5.46E+00
14	57	420	118.0	0.79	0.002	20.64	0.06	23.13	0.29	5.70E-04	3.48E-06	1828	9.10E+00
14	62	360	110.0	0.79	0.005	25.80	0.06	28.47	0.16	6.23E-04	1.24E-05	2115	4.06E+00
14	62	360	109.6	0.79	0.005	25.69	0.08	28.43	0.14	6.36E-04	3.53E-06	2090	4.75E+00
14	63	360	110.1	0.79	0.005	25.95	0.09	28.72	0.15	6.38E-04	3.85E-06	2096	3.66E+00
14	68	360	114.7	0.79	0.005	30.73	0.08	33.63	0.19	6.70E-04	3.81E-06	2483	9.17E+00
14	68	360	118.2	0.79	0.005	30.96	0.07	33.96	0.18	6.87E-04	3.64E-06	2469	3.38E+00
14	68	360	117.9	0.79	0.005	30.83	0.10	33.84	0.20	6.94E-04	3.75E-06	2434	3.38E+00
14	73	360	122.6	0.79	0.005	35.87	0.09	39.08	0.23	7.31E-04	4.02E-06	2794	5.81E+00
14	73	360	125.4	0.79	0.005	35.96	0.08	39.05	0.20	7.44E-04	3.70E-06	2768	3.88E+00
14	73	360	125.2	0.79	0.005	35.65	0.12	38.93	0.22	7.51E-04	3.99E-06	2764	3.35E+00
14	78	300	110.0	0.79	0.006	40.77	0.08	44.31	0.21	7.96E-04	4.26E-06	3123	1.62E+01
14	78	300	110.3	0.79	0.006	40.79	0.12	44.38	0.20	8.19E-04	4.25E-06	3040	3.00E+00
14	79	300	110.5	0.79	0.006	40.92	0.08	44.45	0.24	7.98E-04	4.40E-06	3038	5.69E+00
14	83	300	115.5	0.79	0.007	45.56	0.08	49.33	0.23	8.53E-04	4.04E-06	3501	8.58E+00
14	84	300	115.7	0.79	0.007	45.76	0.09	49.53	0.26	8.54E-04	4.34E-06	3476	3.78E+00
14	84	330	127.8	0.79	0.007	46.08	0.12	50.03	0.23	8.80E-04	4.50E-06	3498	2.01E+00
14	88	300	120.8	0.79	0.007	50.62	0.09	54.78	0.26	9.14E-04	4.09E-06	3780	9.57E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
14	89	300	121.5	0.79	0.007	50.81	0.09	54.96	0.26	9.18E-04	4.67E-06	3782	4.52E+00
14	89	300	121.2	0.79	0.007	50.72	0.15	54.96	0.23	9.32E-04	4.74E-06	3750	3.54E+00
15	23	600	76.4	0.75	0.001	5.96	0.07	6.82	0.09	2.28E-04	7.14E-05		
15	23	600	76.5	0.75	0.001	5.93	0.07	6.77	0.06	2.32E-04	6.79E-05	627	1.30E+00
15	23	600	76.1	0.75	0.001	5.89	0.07	6.77	0.06	2.35E-04	6.66E-05	626	1.38E+00
15	33	600	116.0	0.76	0.002	11.06	0.09	12.31	0.10	3.79E-04	9.88E-05		
15	33	600	115.8	0.76	0.002	11.25	0.08	12.32	0.05	3.83E-04	9.84E-05	1060	1.39E+00
15	33	600	115.7	0.76	0.002	11.19	0.08	12.26	0.14	3.85E-04	9.85E-05	1039	2.21E+00
15	40	540	129.4	0.76	0.003	15.98	0.27	17.54	0.12	4.89E-04	1.22E-04	1403	2.20E+00
15	40	540	129.1	0.76	0.003	16.01	0.10	17.57	0.10	4.92E-04	1.21E-04	1421	2.01E+00
15	40	540	129.0	0.76	0.003	15.92	0.09	17.51	0.13	4.96E-04	1.22E-04	1415	3.22E+00
15	46	480	132.5	0.76	0.004	20.77	0.09	22.78	0.17	5.80E-04	1.40E-04	1780	2.04E+00
15	46	480	132.3	0.76	0.003	20.75	0.10	22.78	0.19	5.84E-04	1.40E-04	1788	2.13E+00
15	46	480	134.0	0.76	0.003	21.24	0.10	23.24	0.15	5.87E-04	2.53E-04	1836	2.12E+00
15	62	420	127.8	0.76	0.004	25.70	0.13	28.09	0.14	6.39E-04	1.54E-04		
15	62	420	127.9	0.76	0.004	25.60	0.12	28.00	0.20	6.53E-04	1.54E-04	2024	3.15E+00
15	62	420	127.8	0.76	0.004	25.57	0.12	27.99	0.19	6.53E-04	1.54E-04	2010	3.50E+00
15	68	360	118.3	0.76	0.004	30.69	0.13	33.47	0.18	7.11E-04	1.76E-04		
15	68	360	118.4	0.76	0.004	30.60	0.13	33.37	0.22	7.20E-04	1.66E-04	2358	3.46E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
15	68	385	126.9	0.76	0.004	30.60	0.12	33.41	0.20	7.22E-04	1.66E-04	2370	3.52E+00
15	73	360	126.9	0.76	0.004	35.69	0.15	38.83	0.24	7.84E-04	1.77E-04	2692	3.37E+00
15	73	360	126.7	0.76	0.005	35.66	0.15	38.85	0.26	7.91E-04	1.77E-04	2694	2.80E+00
15	73	360	126.5	0.76	0.004	35.61	0.15	38.88	0.23	7.98E-04	1.77E-04	2698	3.04E+00
15	78	300	111.8	0.76	0.004	40.73	0.17	44.32	0.29	8.49E-04	1.87E-04		
15	78	300	110.5	0.76	0.004	40.69	0.16	44.31	0.27	8.52E-04	1.85E-04	2950	5.18E+00
15	78	300	112.0	0.76	0.004	40.79	0.15	44.43	0.21	8.57E-04	1.88E-04	2997	5.81E+00
15	84	300	117.8	0.76	0.005	45.54	0.19	49.51	0.27	9.10E-04	1.98E-04	3401	3.21E+00
15	84	300	117.4	0.76	0.005	45.49	0.17	49.49	0.27	9.12E-04	1.98E-04	3397	4.33E+00
15	84	300	117.7	0.76	0.005	45.64	0.16	49.71	0.20	9.18E-04	1.97E-04	3473	6.37E+00
15	88	300	123.1	0.76	0.007	50.60	0.17	55.00	0.30	9.65E-04	2.06E-04	3717	5.76E+00
15	88	300	123.4	0.76	0.006	50.89	0.19	55.36	0.24	9.75E-04	2.07E-04	3872	2.94E+01
15	88	300	123.3	0.76	0.006	50.50	0.17	54.95	0.27	9.78E-04	2.06E-04	3713	5.55E+00
16	23	600	80.9	0.78	0.001	5.97	0.07	6.82	0.06	2.40E-04	7.11E-05	664	2.18E+00
16	23	600	80.6	0.78	0.001	5.78	0.07	6.62	0.06	2.41E-04	7.35E-05	629	1.51E+00
16	23	600	80.8	0.78	0.001	5.86	0.07			2.46E-04	6.95E-05	628	1.39E+00
16	32	600	121.4	0.78	0.002	10.81	0.07	11.84	0.10	3.87E-04	1.14E-04	1030	1.78E+00
16	32	600	121.0	0.78	0.002	10.81	0.07	11.88	0.10	3.87E-04	1.03E-04	1048	1.58E+00
16	32	600	120.1	0.78	0.002	10.75	0.07	11.81	0.09	3.88E-04	1.02E-04	1030	1.75E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
16	40	480	122.4	0.78	0.002	16.16	0.08	17.90	0.12	5.05E-04	1.29E-04	1473	4.48E+00
16	40	540	137.9	0.78	0.002	16.14	0.25	17.86	0.13	5.08E-04	1.29E-04	1447	1.47E+01
16	40	480	122.0	0.78	0.002	16.11	0.07	17.83	0.13	5.09E-04	1.29E-04	1466	2.66E+00
16	56	420	123.7	0.79	0.002	20.99	0.09	23.21	0.19	5.93E-04	1.57E-04	1869	1.05E+01
16	56	480	140.2	0.79	0.002	20.58	0.07	22.76	0.14	5.97E-04	1.53E-04	1782	1.07E+01
16	56	420	122.2	0.79	0.002	20.49	0.09	22.74	0.18	5.98E-04	1.48E-04	1781	1.02E+01
16	62	360	117.8	0.79	0.005	25.78	0.10	28.44	0.15	6.73E-04	1.65E-04	2104	7.50E+00
16	62	360	117.9	0.79	0.005	25.70	0.09	28.34	0.15	6.80E-04	1.65E-04	2069	2.90E+00
16	62	360	117.7	0.79	0.005	25.66	0.10	28.35	0.14	6.81E-04	1.65E-04	2065	3.63E+00
16	68	360	127.2	0.79	0.005	30.45	0.07	33.57	0.17	7.48E-04	1.79E-04	2503	1.10E+01
16	68	360	128.4	0.79	0.005	30.72	0.11	33.86	0.17	7.47E-04	1.79E-04	2452	4.05E+00
16	68	360	128.3	0.79	0.005	30.73	0.10	33.82	0.17	7.50E-04	1.79E-04	2435	3.90E+00
16	73	360	136.5	0.79	0.005	35.39	0.08	39.00	0.18	8.19E-04	1.91E-04	2807	6.67E+00
16	73	300	114.1	0.79	0.005	35.37	0.13	38.93	0.19	8.11E-04	1.91E-04	2778	6.46E+00
16	73	300	113.8	0.79	0.005	35.40	0.11	38.89	0.18	8.13E-04	1.91E-04	2735	2.89E+00
16	79	300	121.4	0.79	0.006	40.79	0.13	44.77	0.20	8.84E-04	2.03E-04	3013	3.60E+00
16	79	300	121.5	0.79	0.006	40.81	0.15	44.84	0.20	8.84E-04	2.03E-04	3076	3.74E+00
16	79	300	121.0	0.79	0.006	40.79	0.09	44.84	0.19	8.90E-04	2.02E-04	3036	5.23E+00
16	84	300	127.7	0.79	0.007	45.59	0.15	50.04	0.20	9.44E-04	2.14E-04	3538	7.86E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
16	84	300	127.5	0.79	0.007	45.59	0.15	49.98	0.19	9.44E-04	2.13E-04	3487	2.98E+00
16	84	300	127.4	0.79	0.007	45.59	0.09	50.05	0.19	9.51E-04	2.13E-04	3520	3.37E+00
16	89	300	133.6	0.79	0.007	50.51	0.16	55.49	0.20	1.01E-03	2.23E-04	3867	3.99E+00
16	89	300	133.3	0.79	0.007	50.56	0.11	55.45	0.23	1.01E-03	2.23E-04	3822	3.52E+00
16	89	300	133.6	0.79	0.007	50.47	0.16	55.40	0.22	1.01E-03	2.23E-04	3804	5.84E+00
17	26	265	128.8	0.76	0.001	5.69	0.07	7.77	0.03	5.94E-04	4.52E-06	826	2.20E+00
17	26	270	130.1	0.76	0.001	5.56	0.07	7.59	0.07	6.03E-04	5.02E-06	778	2.06E+00
17	28	300	134.8	0.76	0.002	5.25	0.13	7.03	0.20	5.48E-04	1.21E-05	867	2.42E+00
17	39	170	129.2	0.76	0.005	11.12	0.09	15.45	0.07	9.56E-04	7.69E-06	1545	2.91E+00
17	39	170	128.7	0.76	0.005	11.05	0.08	15.39	0.07	9.67E-04	7.45E-06	1573	4.43E+00
17	48	190	135.0	0.76	0.005	10.01	0.51			9.35E-04	5.08E-05	2174	1.76E+01
17	55	140	133.5	0.76	0.008	16.54	0.09	23.17	0.10	1.23E-03	9.66E-06	1924	3.88E+00
17	55	140	133.4	0.76	0.008	16.47	0.10	23.18	0.11	1.24E-03	1.02E-05	1933	4.51E+00
17	56	140	132.9	0.76	0.008	16.40	0.10	23.58	0.12	1.28E-03	1.01E-05	2015	3.48E+00
17	65	120	131.4	0.78	0.015	21.43	0.11	30.23	0.10	1.45E-03	2.13E-05	2487	3.32E+00
17	65	120	131.0	0.78	0.015	21.29	0.11	30.20	0.14	1.46E-03	1.27E-05	2485	3.80E+00
17	65	125	135.0	0.77	0.010	20.94	0.12	30.19	0.14	1.47E-03	1.20E-05	2526	6.53E+01
17	73	110	132.8	0.78	0.010	26.16	0.11	36.96	0.12	1.60E-03	2.08E-05	3091	5.16E+00
17	73	110	132.2	0.78	0.010	25.96	0.12	36.83	0.14	1.62E-03	1.46E-05	3092	4.19E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
17	73	110	131.0	0.77	0.015	25.49	0.11	36.77	0.15	1.63E-03	1.46E-05	3117	1.80E+00
17	79	105	136.3	0.77	0.010	30.37	0.12	42.56	0.14	1.71E-03	1.62E-05	3559	3.76E+00
17	79	100	130.5	0.77	0.010	30.68	0.13	43.19	0.16	1.74E-03	1.75E-05	3585	5.59E+00
17	80	100	132.5	0.78	0.020	31.44	0.13	44.09	0.20	1.75E-03	1.72E-05	3568	6.64E+01
17	86	95	133.5	0.79	0.020	35.92	0.12	50.43	0.17	1.89E-03	3.27E-05	3987	1.54E+02
17	86	95	133.9	0.78	0.010	36.06	0.14	50.64	0.16	1.90E-03	1.85E-05	4096	6.11E+00
17	86	95	133.6	0.78	0.010	35.77	0.13	50.50	0.15	1.92E-03	1.90E-05	4107	4.56E+00
17	90	90	134.1	0.79	0.020	40.42	0.15	56.67	0.19	2.00E-03	2.10E-05	4445	6.19E+00
17	91	90	134.9	0.79	0.015	41.08	0.15	57.71	0.18	2.03E-03	2.11E-05	4579	4.80E+00
17	91	90	134.5	0.79	0.015	40.79	0.14	57.61	0.17	2.05E-03	2.08E-05	4580	3.87E+00
17	97	85	133.9	0.79	0.015	45.77	0.15	64.29	0.18	2.15E-03	2.28E-05	5391	4.77E+00
17	97	85	133.4	0.79	0.015	45.46	0.15	64.19	0.20	2.17E-03	2.29E-05	5405	6.64E+00
17	98	85	134.8	0.80	0.020	46.20	0.14	64.96	0.18	2.15E-03	2.86E-06	5524	3.03E+00
17	100	85	139.9	0.80	0.020	48.87	0.17	68.53	0.23	2.21E-03	2.38E-05	5966	7.26E+00
17	100	80	130.5	0.79	0.020	49.22	0.16	69.17	0.21	2.21E-03	2.49E-05	6036	5.20E+00
17	100	80	131.0	0.79	0.020	49.14	0.16	69.21	0.23	2.22E-03	2.51E-05	6084	8.76E+00
18	25	300	132.2	0.79	0.002	4.94	0.06	7.17	0.07	5.61E-04	4.27E-06	744	1.45E+00
18	25	300	132.2	0.79	0.002	4.99	0.06	7.11	0.06	5.61E-04	4.33E-06	740	1.40E+00
18	25	300	132.4	0.79	0.002	4.93	0.06	7.07	0.06	5.63E-04	4.16E-06	742	1.48E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
18	47	165	123.7	0.80	0.005	11.10	0.07	15.88	0.10	9.59E-04	9.19E-06	1468	1.04E+01
18	47	180	134.3	0.80	0.005	11.11	0.07	15.87	0.10	9.60E-04	7.25E-06	1457	4.13E+00
18	47	180	133.8	0.80	0.005	11.07	0.07	15.83	0.09	9.63E-04	7.34E-06	1464	5.61E+00
18	56	140	127.8	0.80	0.010	16.03	0.07	22.67	0.12	1.18E-03	1.32E-05	1934	3.90E+00
18	56	150	136.9	0.80	0.010	16.01	0.07	22.65	0.12	1.18E-03	9.32E-06	1928	2.30E+00
18	56	150	136.7	0.80	0.010	15.95	0.08	22.62	0.11	1.19E-03	9.45E-06	1933	2.68E+00
18	64	125	132.1	0.81	0.010	20.96	0.07	29.49	0.11	1.37E-03	1.20E-05	2408	2.44E+00
18	64	120	127.0	0.81	0.010	20.85	0.08	29.41	0.09	1.38E-03	1.20E-05	2401	2.79E+00
18	65	120	128.0	0.81	0.010	21.40	0.07	30.12	0.10	1.39E-03	1.24E-05	2461	2.49E+00
18	71	110	129.3	0.81	0.010	25.72	0.07	36.00	0.12	1.53E-03	1.46E-05	2990	3.38E+00
18	71	110	129.0	0.81	0.010	25.67	0.07	35.98	0.13	1.53E-03	1.49E-05	2982	3.63E+00
18	71	110	128.7	0.81	0.010	25.53	0.08	35.92	0.12	1.54E-03	1.44E-05	2982	2.01E+00
18	79	100	127.9	0.81	0.010	30.84	0.08	43.09	0.16	1.70E-03	1.69E-05	3465	1.76E+00
18	80	100	130.4	0.81	0.010	32.67	0.07	45.02	0.13	1.69E-03	1.70E-05	3751	6.78E+00
18	81	100	128.4	0.81	0.010	31.10	0.08	43.26	0.15	1.68E-03	1.71E-05	3496	2.99E+00
18	84	95	130.2	0.82	0.015	36.13	0.07	49.60	0.18	1.78E-03	1.88E-05	3976	6.49E+00
18	85	95	130.6	0.82	0.015	36.02	0.08	49.97	0.21	1.82E-03	1.86E-05	3965	4.48E+00
18	88	96	129.8	0.82	0.015	35.52	0.07	49.15	0.18	1.79E-03	1.76E-05	3886	2.98E+00
18	89	90	130.7	0.82	0.015	40.83	0.09	56.31	0.23	1.94E-03	3.17E-05	4352	2.97E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
18	90	90	130.4	0.82	0.015	40.81	0.07	55.82	0.16	1.90E-03	2.09E-05	4527	5.62E+00
18	90	90	129.1	0.82	0.015	40.26	0.08	55.46	0.19	1.91E-03	2.04E-05	4462	4.63E+00
18	95	85	130.0	0.79	0.005	46.00	0.09	63.24	0.24	2.06E-03	2.26E-05	5203	3.95E+00
18	98	85	129.5	0.82	0.015	45.58	0.07	62.24	0.20	2.01E-03	2.79E-05	5271	3.86E+00
18	98	85	130.1	0.79	0.005	46.11	0.09	63.38	0.31	2.06E-03	2.22E-05	5200	5.32E+00
18	100	80	127.8	0.82	0.015	50.88	0.08	69.57	0.40	2.13E-03	7.14E-05	6050	6.66E+00
18	100	80	128.2	0.82	0.015	50.76	0.09	69.58	0.37	2.15E-03	3.42E-05	6013	4.43E+00
18	100	80	128.0	0.82	0.015	50.64	0.10	69.49	0.27	2.16E-03	2.47E-05	6006	2.60E+00
19	26	265	129.3	0.76	0.002	5.98	0.06	7.80	0.04	5.83E-04	2.44E-04	781	1.09E+00
19	26	265	128.7	0.76	0.002	5.92	0.07	7.67	0.07	5.86E-04	2.44E-04	769	1.24E+00
19	26	270	129.6	0.76	0.002	5.85	0.06	7.63	0.07	5.96E-04	2.40E-04	765	1.56E+00
19	29	175	129.9	0.76	0.010	11.05	0.08	14.77	0.06	9.14E-04	3.69E-04	1018	1.81E+00
19	29	175	128.9	0.76	0.010	10.93	0.08	14.69	0.08	9.30E-04	3.66E-04	1007	1.65E+00
19	29	180	132	0.76	0.010	10.87	0.08	14.65	0.08	9.36E-04	3.65E-04	1004	2.59E+00
19	56	140	129.9	0.76	0.010	16.00	0.10	21.94	0.09	1.17E-03	4.59E-04	1925	2.12E+00
19	56	140	128.5	0.76	0.010	15.84	0.09	21.90	0.20	1.18E-03	4.54E-04	1922	1.16E+01
19	56	145	133	0.76	0.010	15.79	0.10	21.83	0.18	1.19E-03	4.54E-04	1919	3.26E+00
19	63	125	132.9	0.76	0.010	20.77	0.10	28.32	0.06	1.33E-03	5.27E-04	2460	3.24E+00
19	64	125	131.9	0.76	0.010	20.49	0.09	28.32	0.11	1.36E-03	5.21E-04	2354	1.66E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
19	64	125	132.3	0.76	0.010	20.63	0.11	28.67	0.12	1.39E-03	5.23E-04	2408	2.21E+00
19	71	110	130.7	0.76	0.010	25.70	0.11	35.16	0.10	1.50E-03	5.85E-04	2965	3.13E+00
19	72	110	130.5	0.76	0.010	25.52	0.12	35.23	0.13	1.54E-03	5.84E-04	2899	2.04E+00
19	72	110	130.6	0.76	0.010	25.62	0.12	35.58	0.16	1.56E-03	5.85E-04	2917	2.22E+00
19	78	105	136.8	0.76	0.010	30.76	0.13	42.57	0.16	1.70E-03	6.41E-04	3393	2.40E+00
19	78	100	129.6	0.76	0.010	30.55	0.12	42.49	0.16	1.72E-03	6.37E-04	3402	2.13E+00
19	79	100	129.3	0.76	0.010	30.74	0.12	42.90	0.17	1.73E-03	6.35E-04	3459	1.85E+00
19	84	95	132	0.77	0.012	35.53	0.13	48.76	0.09	1.80E-03	6.83E-04	3834	4.59E+00
19	84	95	132.2	0.77	0.012	35.32	0.13	48.86	0.14	1.83E-03	6.83E-04	3792	3.82E+00
19	85	95	133.1	0.77	0.012	35.76	0.13	49.67	0.16	1.87E-03	6.88E-04	3914	4.45E+00
19	90	85	126.9	0.77	0.015	41.01	0.16	56.95	0.20	2.00E-03	7.32E-04	4443	3.41E+00
19	90	90	133.9	0.77	0.015	40.82	0.13	56.83	0.16	2.01E-03	7.29E-04	4440	1.69E+00
19	93	90	133.8	0.77	0.015	40.61	0.14	56.09	0.18	1.97E-03	7.29E-04	4554	2.43E+00
19	96	85	133	0.78	0.020	45.19	0.15	62.37	0.22	2.08E-03	7.66E-04	5284	3.10E+00
19	96	85	133.2	0.78	0.020	45.64	0.15	63.07	0.19	2.11E-03	7.67E-04	5340	5.23E+00
19	96	85	133.3	0.78	0.020	45.46	0.15	63.03	0.22	2.11E-03	7.75E-04	5356	6.58E+00
19	100	80	131.4	0.78	0.025	50.38	0.16	69.42	0.21	2.19E-03	8.03E-04	6100	2.49E+01
19	100	80	130.7	0.78	0.025	50.19	0.17	69.31	0.22	2.20E-03	7.98E-04	6015	5.47E+00
19	100	80	129.9	0.78	0.025	49.77	0.18	68.98	0.22	2.20E-03	7.94E-04	6027	6.23E+00

$\boldsymbol{G}$	$\boldsymbol{Pump}$ (%)	$\boldsymbol{T}$ $(\boldsymbol{s})$	$\boldsymbol{M}$ $(\boldsymbol{kg})$	$\boldsymbol{h_{ext}}$ $(\boldsymbol{m})$	$\boldsymbol{\delta h_{ext}}$ $(\boldsymbol{m})$	$\boldsymbol{h_{leak}}$ $(\boldsymbol{m})$	$\boldsymbol{\delta h_{leak}}$ $(\boldsymbol{m})$	$\boldsymbol{h_0}$ $(\boldsymbol{m})$	$\boldsymbol{\delta h_0}$ $(\boldsymbol{m})$	$\boldsymbol{Q}$ $(\boldsymbol{m^3/s})$	$\boldsymbol{\delta Q}$ $(\boldsymbol{m^3/s})$	$\boldsymbol{E_{elec}}$ $(\boldsymbol{W})$	$\boldsymbol{\delta E_{elec}}$ $(\boldsymbol{W})$
20	23	310	132.2	0.79	0.002	4.85	0.07	6.33	0.06	4.99E-04	2.14E-04	659	1.39E+00
20	23	310	131.5	0.79	0.002	4.75	0.07	6.18	0.06	5.07E-04	2.14E-04	643	2.32E+00
20	23	310	131.6	0.79	0.002	4.77	0.07	6.15	0.07	5.09E-04	2.14E-04	637	1.52E+00
20	25	200	135.1	0.79	0.005	8.11	0.08	11.50	0.07	8.27E-04	3.37E-04	838	5.80E+00
20	25	195	131.9	0.79	0.005	8.12	0.08	11.50	0.06	8.30E-04	3.37E-04	836	6.35E+00
20	25	200	134.6	0.79	0.005	8.04	0.07	11.45	0.16	8.37E-04	3.35E-04	839	4.60E+00
20	47	165	134.1	0.80	0.005	11.14	0.08	15.74	0.07	1.01E-03	4.04E-04	1463	1.13E+01
20	47	160	130.6	0.80	0.005	11.12	0.08	15.74	0.08	1.02E-03	4.05E-04	1464	1.31E+01
20	47	165	134.4	0.80	0.005	11.00	0.08	15.67	0.07	1.03E-03	4.05E-04	1445	1.09E+01
20	57	125	127.0	0.80	0.010	15.80	0.09	23.04	0.14	1.27E-03	5.02E-04	1992	4.46E+00
20	57	130	131.5	0.80	0.010	15.84	0.09	23.02	0.10	1.27E-03	5.00E-04	1984	5.10E+00
20	57	135	136.5	0.80	0.010	15.68	0.10	22.95	0.13	1.28E-03	5.00E-04	1980	8.04E+00
20	65	110	128.6	0.81	0.010	20.72	0.11	30.28	0.13	1.48E-03	5.76E-04	2566	7.42E+00
20	66	110	129.4	0.81	0.010	21.05	0.09	30.84	0.13	1.50E-03	5.80E-04	2582	2.82E+00
20	66	115	135.1	0.81	0.010	20.90	0.12	30.76	0.15	1.51E-03	5.79E-04	2563	3.11E+00
20	74	100	130.2	0.81	0.010	25.71	0.10	37.63	0.12	1.67E-03	6.40E-04	3166	3.11E+00
20	74	100	130.0	0.81	0.010	25.57	0.08	37.53	0.12	1.67E-03	6.39E-04	3137	3.13E+00
20	74	100	129.1	0.81	0.010	25.50	0.11	37.49	0.12	1.68E-03	6.35E-04	3136	2.30E+00
20	80	90	126.7	0.81	0.010	30.47	0.08	44.31	0.14	1.81E-03	6.90E-04	3733	7.90E+00

G	$Pump$ (%)	T (s)	M (kg)	h_{ext} (m)	δh_{ext} (m)	h_{leak} (m)	δh_{leak} (m)	h_0 (m)	δh_0 (m)	Q (m^3/s)	δQ (m^3/s)	E_{elec} (W)	δE_{elec} (W)
20	81	95	134.6	0.81	0.010	30.73	0.10	44.91	0.16	1.83E-03	6.96E-04	3724	2.53E+01
20	81	95	134.4	0.81	0.010	30.78	0.10	44.94	0.16	1.83E-03	6.95E-04	3739	5.06E+00
20	88	90	135.3	0.82	0.015	35.55	0.09	51.65	0.15	1.95E-03	7.37E-04	4342	6.48E+00
20	88	85	128.6	0.82	0.015	35.46	0.10	51.77	0.16	1.97E-03	7.42E-04	4345	5.73E+00
20	88	90	135.8	0.82	0.015	35.81	0.11	52.27	0.17	1.98E-03	7.40E-04	4412	7.92E+00
20	92	80	127.7	0.82	0.015	40.37	0.10	58.59	0.15	2.09E-03	7.80E-04	4820	5.28E+00
20	92	85	135.8	0.82	0.015	40.74	0.12	59.31	0.17	2.11E-03	7.82E-04	4904	5.40E+00
20	93	80	128.1	0.82	0.015	40.76	0.12	59.28	0.16	2.11E-03	7.83E-04	4895	4.12E+00
20	98	75	126.0	0.82	0.015	45.16	0.08	65.68	0.18	2.21E-03	8.20E-04	5733	4.42E+00
20	100	75	128.4	0.82	0.015	47.36	0.13	68.60	0.17	2.23E-03	8.36E-04	6051	1.20E+01
20	100	80	136.8	0.82	0.015	47.27	0.12	68.62	0.21	2.23E-03	8.36E-04	6043	6.90E+00
20	100	80	136.4	0.82	0.015	47.07	0.11	68.53	0.18	2.23E-03	8.33E-04	6062	5.15E+00