UNIVERSITI PUTRA MALAYSIA

EXPERIMENTAL AND COMPUTATIONAL FLUID DYNAMICS INVESTIGATION ON THE PERFORMANCE OF LEAKAGE SENSOR MODEL

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By

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Water is an extremely important natural resource and fresh water management need to be handled in a systematic and efficient way so that fresh water supply always sufficient for the ever-growing population. In the Arabian Gulf, the scarcity of fresh water causes the authority to use the desalination technology to convert the salt water into water that suitable for the human consumption. This technology comes with a high cost and it is important to detect pipe leakage to avoid wastage of the water. Hence, the current work aim is to propose a new leakage detector shape and analyse the performance using CFD simulation and an experimental work. Mobility module of Design 4 has been designed and developed base on the aerodynamics performance of the earlier design mobility module. The design hydrodynamics performance also been investigated via experimental work and it has a preferable performance when simulated in the real pipe condition to detect leakage in the pipeline. Design optimization has been carried out to further improve the performance of the mobility module to be working in the real pipe condition. The basic shape is fixed as the same as the mobility module that has been chosen in the previous comparison. The design hydrodynamics performance also been investigated via CFD simulation. Data from simulation analysis has shown that the determination of domain locations affected the numerical calculation results. Identification of mesh size and mesh type will produce accurate results such as implementation of refining mesh focusing on potential turbulent flow area will obtain more smoothness results. The selection of a proper turbulent model also will influent the result. Finally, the design performance been assessed via parametric study. The parametric study shows the effects of upstream velocity and model design on the variation of drag force. Based on the comparisons between the results obtained through numerical analysis, it can be concluded that the drag force of leakage sensor increases

direct proportionally with the upstream flow velocity. There is no significant different between modified design 1 and design 2 in the simulation procedure but both results are 3 times higher than original best design which is 300% improvement from experimental procedure in all upstream velocity.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

SIASATAN EKSPERIMEN DAN PENGIRAAN DINAMIK BENDALIR TERHADAP PRESTASI MODEL PENGESAN KEBOCORAN

Oleh

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Air merupakan sumber semula jadi yang sangat penting dan pengurusan air tawar perlu dikendalikan dengan cara yang sistematik dan cekap supaya bekalan air tawar sentiasa mencukupi untuk populasi yang semakin meningkat. Di Teluk Arab, kekurangan air tawar menyebabkan pihak berkuasa menggunakan teknologi penyahgaraman untuk menukar air masin kepada air yang sesuai untuk kegunaan manusia. Teknologi ini datang dengan kos yang tinggi dan adalah penting untuk mengesan kebocoran paip untuk mengelakkan pembaziran air. Oleh itu, matlamat kerja semasa adalah untuk mencadangkan bentuk pengesan kebocoran baharu dan menganalisis prestasi menggunakan simulasi CFD dan kerja eksperimen. Modul mobiliti Reka Bentuk 4 telah direka bentuk dan dibangunkan berdasarkan prestasi aerodinamik modul mobiliti reka bentuk terdahulu. Prestasi hidrodinamik reka bentuk juga telah disiasat melalui kerja eksperimen dan ia mempunyai prestasi yang lebih baik apabila disimulasikan dalam keadaan paip sebenar untuk mengesan kebocoran dalam saluran paip. Pengoptimuman reka bentuk telah dijalankan untuk meningkatkan lagi prestasi modul mobiliti untuk berfungsi dalam keadaan paip sebenar. Bentuk asas ditetapkan sama seperti modul mobiliti yang telah dipilih dalam perbandingan sebelumnya. Prestasi hidrodinamik reka bentuk juga telah disiasat melalui simulasi CFD. Data daripada analisis simulasi telah menunjukkan bahawa penentuan lokasi domain mempengaruhi keputusan pengiraan berangka. Pengenalpastian saiz jejaring dan jenis jejaring akan menghasilkan keputusan yang tepat seperti pelaksanaan mesh penapisan yang memfokuskan kawasan aliran turbulen berpotensi akan memperoleh hasil yang lebih lancar. Pemilihan model turbulen yang betul juga akan mempengaruhi hasilnya. Akhir sekali, prestasi reka bentuk telah dinilai melalui kajian parametrik. Kajian parametrik menunjukkan kesan halaju huluan dan reka bentuk model terhadap variasi daya seret. Berdasarkan perbandingan antara keputusan yang diperoleh

melalui analisis berangka, dapat disimpulkan bahawa daya seret sensor kebocoran meningkat secara berkadar terus dengan halaju aliran hulu. Tidak terdapat perbezaan yang signifikan antara reka bentuk 1 dan reka bentuk 2 yang diubah suai dalam prosedur simulasi tetapi kedua-dua keputusan adalah 3 kali lebih tinggi daripada reka bentuk terbaik asal iaitu 300% peningkatan daripada prosedur eksperimen dalam semua halaju.

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To my wife thanks for your patience while I complete this study. Thanks also to my children, which serves as part of my inspirations in writing out this research.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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LIST OF ABBREVIATIONS

AF	accelerating flow
ALE	arbitrary lagrangian eulerian
avg	average
BD	blended bifferencing
BF	boundary fitted
CD	central cifferencing
CFD	computational fluid dynamics
CPU	central processing unit
CT	computed tomography
CURVIB	curvilinear immersed boundary method
DES	detached eddy simulation
DF	decelerating flow
DFG	Deutsche Forschungsgemeinschaft (German Research Association)
DNS	direct numerical simulation
DWDN	Drinking Water Distribution Networks
EFD	experimental fluid dynamics
FCT	flux corrected transport
FD	fictitious domain
Fs	safety factor
FVM	finite volume method
GCI	grid convergence index
IB	immersed boundary
IIM	immersed interface method

IMM	immersed membrane method
LBM	lattice boltzman method
LES	large eddy simulation
LUD	Linear upwind differencing
MPI	message passing interface
MULES	Multi-dimensionsal limiter for explicit solution
NBF	non-boundary fitted
NBF-VOF	non-boundary fitted/volume of fluid
PDEs	partial differential equations
PF	peak flow
PIV	particle image velocimetry
PLIC	piecewise linear interface construction
RANS	reynolds average navier stokes
RBC	red blood cell
RC	right coronary
RSS	reynolds shear stress
WDN	Water Distribution Network

CHAPTER 1

INTRODUCTION

1.1 Overview

Water leakage is one of the main concerns in the water piping system. The occurrence of leaks may be the consequence of several reasons including damage and manufacturing flaws, bad workmanship, sudden changes of pressure, cracking, internal and external corrosion, and defects in pipes or lack of maintenance [1]. Usually, the leakage from external pipes is easily detected. Normally it is done through visual inspection and the use of some bulky devices. However, underground pipes pose a different challenge in order to detect the leaks and this is where tiny in-pipe sensor should come handy. Underground drainage due to leaks may result in problems such as damage to building and structure, deterioration of building materials, soil erosion and contaminants infiltrating from the leaky pipe [2].

Water pipeline leakage can be apparent when the water penetrates the layer above the damaged location and emerge on the ground surface. It can also be hidden and only become noticeable when the water swells through the sewerage system or the pipeline networks. Some of the most frequent causes of pipeline damages are the application of improper pipes, hard contact on the pipes, ground deformations, corrosion or erosion of the inner wall of the pipes and ageing polymer materials [3].

A lot of research has been done to come up with an optimum water pipeline leakage detection system which has the best consideration of the accuracy, cost, response time, informative and durability. Every each of the leak detection methods has its own apparent advantages but it also has the trade-off characteristics which created the gap for further improvisation. By using a free-mobile sensor module in the pipeline, several limitations faced by other leakage detection methods have been overcome. A sensor leakage module's in the water pipeline ideal specifications are the self-autonomous, high leak sensing sensitivity, excellent working conditions, effective communication, and highly localized. Figure 1.3 show an example of leakage detector device.

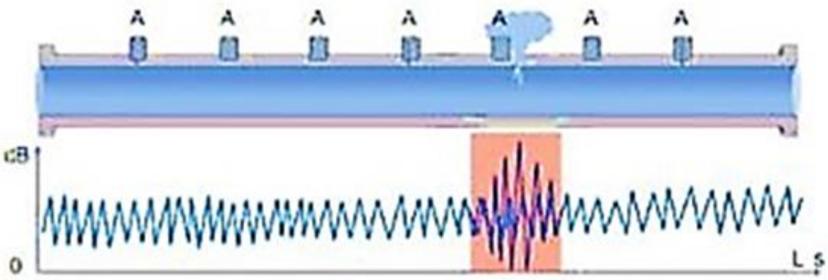

Figure 1.1: Leakage detector device [4]

From the literature review, the design requirements those for an optimum leakage module design are the size, mobility, free-floating ability, speed control and the stability. It is claimed that a mobility module has to be in ideal size for instrumentation of data acquisition as well as for the flight path in the water pipeline to be non-invasive. The aerodynamic external design has to fulfil the need forthe mobility module to slow down at the location of the leakage to collect reliable data of the leakage. To achieve this, its velocity needs to be induced to be in the same speed as the flow or lower and has stable orientation. These theoretical baselines are compared to the numerical analysis results by using Computational Fluid Dynamics simulation of the mobility module design for validation.

It is a well-known fact that the experimental validation is compulsory and needed as there is no experimental investigation that has been done. The aerodynamic behaviour of the model in the experimental work is crucial as the sensor module will be working in the real condition with disturbances and uncontrollable parameters while computer simulation is the ideal condition of the working conditions. In addition, the prototype should also be tested in the aspect of sustainability, to check whether it can cope with the working environment or the real application for water inspection companies which is in a 100mm diameter water pipeline usually located near the reservoir.

1.2 Problem Statement

Water is an extremely important natural resource not only for drinking, but also for agriculture, industrial usage, tourism, and domestic usage (cooking, hygiene, etc). Fresh water management need to be handled in a systematic and efficient way so that fresh water supply always sufficient for the ever-growing population. In the Arabian Gulf, the scarcity of fresh water causes the authority to use the desalination technology to convert the salt water into water that suitable for the human consumption. This technology comes with a high cost and therefore it is important that the desalinated water meet certain criteria for the human consumption.

The WHO guidelines for drinking water quality states that, water free from turbidity, color, odor, objectionable taste and at a reasonable temperature is said to potable water [4, 5]. The distribution pipelines in case of urban water supply need to monitored for contaminants such as microbial growth, internal corrosion of the pipe's material and other deposits. These contaminants not only affect the quality of the water, but also the smoothness of the water pipe flow due to the pressure loss and additional frictions. This problem also can cause chronic renal issues if it is used directly for drinking or even cooking [4, 5, 7]. Figures 1.4 shows a typical water treatment plant setup. From the figure, it can be seen that the fresh water is treated before it can be distributed to the residential area. This treated fresh water however to be carefully channeled to the users as two problems can occur. The first problem is the pollution of the water ways by the contaminants which has been discussed earlier. The second problem is the underground pipes leakage. As mentioned in section 1.1, the occurrence of leaks may be the consequence of several reasons including damage and manufacturing flaws, bad workmanship, sudden changes of pressure, cracking, internal and external corrosion, and defects in pipes or lack of maintenance. Both problems are the main causes to the wastage of the scarce water resource.

The water that has been produced and lost before it reaches the customer is termed as Non Revenue Water (NRW). In Malaysia specifically, more than 4.27 billion liters of treated water are leaking out of the country's ageing pipe system every day as of 2014. It is quite astonishing to note that this figure alone was enough to fill more than 1,700 Olympic-sized swimming pools or supply Perlis' water demand for 53 days [7]. The worst part is that it will cost a whopping RM 500000 to replace just 1 km of 44000 km-long asbestos-cement pipes nationwide [8]. Thus, proper management of pipeline leakage is deemed to be the most realistic option that is applicable in the near future although old pipe replacement is a must. Water pipeline leakage can be apparent when the water enter penetrates the layer above the damaged location and emerge on the ground surface. It can also be hidden and only become noticeable when the water swells through the sewerage system or the pipeline networks. Some of the most frequently found factors of pipeline damages are the application of improper pipes, hard contact on the pipes, ground deformations, corrosion or erosion of the inner wall of the pipes and ageing polymer materials.

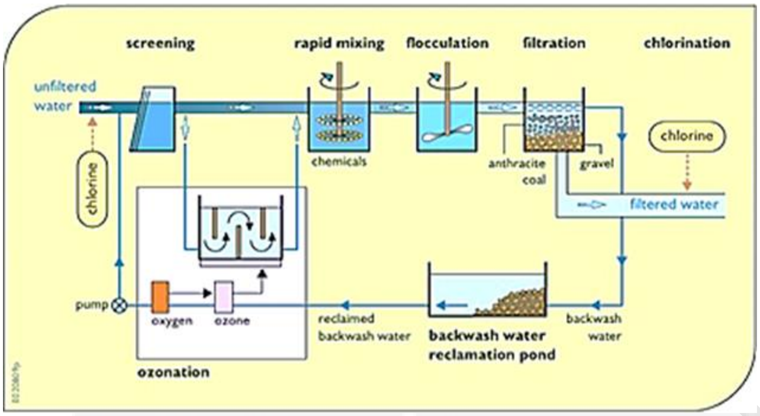

Figure 1.2: Typical water treatment plant setup [9]

The works on water pipeline leakage have been explored by many since the turn of the century. A handful of techniques to detect leaks in water pipeline are practiced in the industry such as water audits by metering, listening devices, leak noise correlators, pressure transients, tracer gas technique, thermography and ground-penetrating radar. For example, Roy [10] has patented the usage of leak noise correlators which are portable microprocessor-based devices that use the crosscorrelation method to pinpoint leaks automatically. Meanwhile Hunaidi [11] performed leakage sensing works by using sensitive mechanisms or materials such as piezoelectric elements to sense leak-induced sound or vibration. Aside from the methods mentioned above, non-acoustic approaches such as tracer gas technique (TGT), infrared thermography and ground-penetrating radar (GPR) have also been touted as potential leak detection methods according [12]. Another popular nonacoustic method reviewed is ground-penetrating radar (GPR) which is suitable for buried underground pipes [13]. Lately, inspection robots have become the area of interest for in-pipe leakage inspection which is compatible for underground pipelines. Liu [14] reviewed the usage of miniature robots for video and laser check-up by Inspector Systems. Another breakthrough in robotic system pipe inspection has been developed by a team of researchers called PipeGuard [15] at assachusetts

Institute of Technology (MIT). The robot looks like an enlarged badminton shuttlecock made up of rubbery materials and soft membrane. The application is simple enough that it can be inserted into the water system through any fire hydrant and then retrieved using a net at another hydrant. Jamoussi [16] have presented in his paper on the fundamental requirements of such systems include the ability to traverse the entire pipe in a reasonable time without getting stuck; ability to inspect the pipe with acceptable accuracy and resolution, and ability to transmit the inspection data to the outside for reporting or save the data locally for later retrieval. According to Chatzigeorgiou [17], the ideal specifications of a sensor module should take into account the characteristics such as autonomy, leak sensing sensitivity, working conditions, communication and localization. Bond [18] presented a tethered system that pinpoints the location and estimates the magnitude of the leak in large diameter water transmission mains of different construction types. Carried by the flow of water, the system can travel through the pipe and in case of a leak; the leak position is marked on the surface by an operator, who is following the device.

One of the famous internal detections is the Pipeline Inspection Gauge (PIG). But the shape of this device is cylindrical and therefore can cause blockage especially at the bends of deformation. The latest approach in internal detection is spherical shape un-tethered ball. This approach is flexible and can flow easily. However, this device also unable to move according to the intended direction especially at the T-Junction, Y-Junction and complicated bends. Therefore, the current work proposed a novel design for the leakage detection device inside pipe flow. The work will focus on the aerodynamics shape and mechanism so that it can travels through T-Junction and other complicate bends with ease. Computational Fluid Dynamics will be used to investigate the effects of the device on the pipe flow.

In the current study, a new shape of leakage sensor inserted into the pipeline is proposed. CFD simulations are used to check the performance of the design. The main parameter that indicates its performance is the drag parameter. Significance of this study is can be noticed on the environment well-being. This is reflected by stopping water from permeating into the ground by detecting the leaks in the pipe earlier so that preventive actions can be done. As a result, the risk of soil erosion and can be diminished as the accumulation of water in the ground from pipes that have burst can be associated with the movement of property and the property grounds. Landslide may seem a much larger scale of something that could happen but the principle is much the same.

Finally, water companies can greatly benefit from the latest advancement of technology in dealing with water pipeline leak detection. The introduction of a new method in this field would provide a better and much improved alternative to the existing methods that have been used for quite some time. It may cut down the cost of operation for leaks detection which means that the budget can be better spent for other purposes. In the long term, the companies may increase the net revenue just by simply reducing the losses and improving the quality and effectiveness of the water distribution system.

1.3 Objectives

The current work aim is to propose a new leakage detector shape and analyze it using CFD simulation and an experimental work.
To achieve the aim of the study, the objective must be achieved as described below:

1. To design and develop a new leakage detector shape based on the aerodynamics performance
2. To investigate hydrodynamics performance of the leakage detector in the flowing water inside the pipe via experimental work and CFD simulation.
3. To assess the performance of the design via the parametric study.

1.4 Scope of Work

The current work focuses on proposing a new design of leakage detection device to be used inside the pipe flow. The scopes of the work are as follow:

1. The experimental work will conduct inside water pipe flow.
2. The instrument available in the laboratory is the high-speed camera.
3. The roughness and other piping parameters are not being considered in the study.
4. The simulation will be using Computational Fluid Dynamics namely Ansys software.
5. The turbulence model applied will be the same as suggested by the previous researcher, therefore no parametric study of the turbulence model.
6. The sensor module's CFD aerodynamics characteristics result and flow simulation are to be compared to the result of it under real internal flow, in the water pipeline condition.

1.5 Thesis Organization

The background of water network system and leakage detection of pipeline introduced in Chapter 1. Motivation for the study, the scope outline and research objectives were also been highlighted. The literature available on the experimental work and CFD studies related to pipe flow and leakage detection method for pipeline summarised in Chapter 2. A detailed review has been discussed in this chapter and it including various studies of different parametric study and experimental studies.

In Chapter 3, the experimental and numerical methodology used for conducting the validation study, including the numerical methodology followed to carry out the parametric study been explained. Chapter 4 reports the experimental and numerical, results. The verification and validation of the results is reported and discussed in this chapter. The results of the parametric study are also discussed. Finally, Chapter 5 concludes the finding of the current work.

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