AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING
MECHATRONICS ENGINEERING DEPARTMENT

1D Modeling of Heat Transfer in Duct Networks Using Two-Ports

A Thesis submitted in partial fulfillment of the requirements of the

M.Sc. in Mechanical Engineering

By

Weam Shereen Abass Elsahar

B.Sc., Mechanical Engineering, Mechatronics Section
Ain Shams University, 2010

Supervised by

Associate Prof. Dr. Tamer Elnady

Associate Prof. Dr. Wael Akl

Cairo – (2014)

AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING

1D Modeling of Heat Transfer in Duct Networks Using Two-Ports

By

Weam Shereen Abass Elsahar

B.Sc., Mechanical Engineering, Mechatronics Section
Ain Shams University, 2010

EXAMINERS COMMITTEE

Name	Signature
Prof. Farid Abdelaziz Tolba	………………….
Prof. Mats Åbom	………………….
Associate Prof. Tamer Mohamed Elnady	………………….

Date: …. /..…/……………….

STATEMENT

This thesis is submitted as a partial fulfillment of M.Sc. degree in Mechanical engineering, Faculty of Engineering, Ain Shams University.

The author carried out the work included in this thesis and no part of it has been submitted for a degree or qualification at any other scientific entity.

Signature

………………..

Student name

Weam Shereen Abass Elsahar

Researcher Data

Name : Weam Shereen Abass Elsahar

Date of birth : 06/02/1989

Place of birth : Saudi Arabia

Academic Degree : B.Sc., Mechanical Engineering

Field of specialization : Mechatronics

University issued the degree : Ain Shams University

Date of issued degree : 2010

Current Job : Teacher Assistant, Mechatronics Department, Faculty of Engineering, Ain Shams University

Abstract

Several engineering applications require formulating models to describe sound propagation inside ducts and duct networks. Two-port transfer matrix method is commonly used to describe the sound transmission along the system, the same theory was also used to model fluid flow inside pipe networks, and coupling these with the acoustic multiport models added more accuracy to the results. The fluid temperature inside each element in the system has to be known as it influences both the flow and acoustics calculations. One method to calculate the temperature distribution is to generate mean value models for the temperature gradient inside each element of the exhaust system, by integrating these 1D models into the two-port transfer matrix and applying the same calculation algorithms used in flow and acoustics calculations, a realistic model for the temperature drop along the system is obtained which can be used in flow and acoustics. This work intends to create mean value temperature models for different elements of exhaust systems, implement these models into a two-port transfer matrix form, verify them against FEM models and compare the results with real systems measurements.

Acknowledgment

All the literature in the world will never clear my debts toward my advisors, colleges and family members who have supported me through my thesis journey.

My main supervisor Dr. Tamer Elnady I owe to him everything I know about research, I will never be able to thank him enough. I thank him for the healthy research environment he facilitated for me and my colleagues. His devotion to enhance the research and education activities his is responsible for inspires us all. I thank him for making this attitude becoming part of me now.

I would also like to thank Dr. Adel Elsabagh, having his office always open for anyone seeking help, from undergraduates to his peers, I can't recall how many times he helped me in my work.

I would like to thank Dr. Wael Akl my second supervisor for his objective feedback, from which I have learned to view my own work in a critical way.

I find myself obliged to thank Ahmed Okasha for always offering me a third hand in my experimental work, Ahmed Barakat for his educated advice and mind teasing discussions and Mina for withstanding the annoying guy next desk I am.

I would like to thank Mohamed Talat the rescue guard in our lab and Ahmed Yehia for making all my SIDLAB wishes come true.

Maaz faroouqi and Ali zain thank you for dragging me out of work for some off time, without you friends I would have finished my thesis 15 months earlier.

I would like to thank Mohamed Elgendy, Madam Fatma, Mostafa Ali and Mohamed Mostafa for not making us worry about any logistics and helping us to only concentrate on our research work.

Finally I would like to thank my parents, especially my mother for bearing with me while treating home as a free dormitory and restaurant that I usually access late every night, and I apologies for that confusion I caused them when they were asked "what does your son do for living?". I would like to thank my brother for always being there in my off times.

Contents

Chapter 1:
Introduction

Several engineering applications require modeling mass and heat transfer in duct networks. Knowing a good estimation of different physical values in any pipe system helps engineers to design, operate, maintain and control these systems. A good example of a duct network is the exhaust system of a vehicle. Engineers are required to design these exhaust systems considering recent legalizations that require lower noise and gaseous emissions. They also need to satisfy customer demands for the vehicles to be more economic and efficient. For example, it is required to simulate the pressure drop introduced by different elements of an exhaust system to minimize engine backpressure and hence enhancing performance. Similarly, an exhaust system temperature model is essential to design a control system that can optimize fuel consumption, turbochargers performance, catalysts efficiency, warm up time, etc. On the other hand, acousticians need to incorporate models for flow speed and temperature in different regions of the mufflers in order to model their acoustic performance.

Similarly, duct networks in various applications require modeling and simulation tools for thermal and flow simulations. These tools are usually tailored to serve a certain range of applications. Several factors affect the validity of using a certain simulation tool for the duct network under study. Each application requires a certain model that can use the available input parameters and produce the required physical values within a defined accuracy for these results. Other factors include network size and complexity, the geometrical scale of the model, the type and state of the fluid flowing in the network. In addition to all these factors, the differentiation between calculation time and the accuracy of results should be considered to select the suitable simulation tool for the network under study.

In this chapter, a literature review on the different approaches to model the temperature distribution in pipe flow networks is schemed. The first section of this review discusses different methods to model temperature distribution in pipe networks in general. The second section focuses on reviewing previous work related to one dimensional models and average models in pipes. The third section discusses some work related to the effect of applying these models with other physics domains; the interest in this part was directed to these models effects on exhaust systems hydraulic models, acoustics models and flow calculations in pipeline networks. The last section of this review discusses some of the commercial pipe simulation software, their features and the theory behind the models implemented in them. Enlightened by these reviews, the objective of this work is stated showing the procedure followed to produce and investigate the validity of the proposed model.

1.1. Thermal models in pipes

The basic set of equations required for modeling the physics of pipeline flow were summarized by Modisette in [1]. To understand the behavior of a hydraulic pipeline one has to define the forces, the motion and the energy transformation occurring inside the pipe. This physical behavior can be described by the set of equations representing the conservation of mass (continuity), momentum and energy. Some literature also refers to these three equations as Euler equations. Solving these differential equations for a pipe accompanied with the equation of state will result in a full model for the state of the fluid in the pipe. The author here referred to Modisette [2] to define the equation of state for different types of fluids. The result of this solution is the pressure, the velocity, the temperature and the density of the fluid over the pipe domain, also the variation of these values over time can be obtained if a transient solution is considered.

In a later work, Modisette [3] listed different numerical approaches that can be used to produce a thermal model for the flow in pipelines. The first model is the isothermal approximation; in this approach it is usually assumed that the temperature is constant all over the pipeline. Another way to apply this is to assume a certain profile for the temperature over the pipeline, this guess is usually an educated guess based on experience in the field of application and this might not be available in most of the cases.

The second approach is based on a succession of steady state solutions for the system. In order to obtain a transient solution for this model, the energy equation is solved, as for a steady state solution, over a small interval of time. The main drawback of this model is that the energy equation is not properly coupled with other Euler equations affecting the accuracy of the results.

The third approach listed here is the leapfrog transient model. This model is based on alternating the solution of the thermal and the hydraulic equations. The hydraulic model uses previous values of temperature from the last solution of the thermal model and the thermal model uses the last values of pressure and the flow rate calculated from the hydraulic model. This model is more convenient to use for industrial applications as it consumes less computation time.

The last model mentioned in this paper was the full model (Coupled Transient Thermal and Hydraulic Model). In this model, the three differential equations for the conservation of mass, momentum and energy, are solved simultaneously for the whole pipeline system. The author suggested that such approach is not practical to use in the pipeline industry as the solution is time consuming and computationally expensive.

1.2. One dimensional thermal models in pipes

To solve a thermal model in a pipeline network, some simplified approaches are usually used, such as one dimensional (1D) modeling based on averaging the thermal properties over the pipe cross section, and transforming the elements of the pipeline network into lumped parameters or solving the network using some kind of circuit analogy.

Gasser et al. [4] introduced a model for the gas dynamics in an exhaust pipe by solving the set of partial differential equations (PDEs) describing the 1D gas flow dynamic equations of the conservation of mass, momentum and energy. This model was obtained separately for each pipe and then the coupling between the 1D models was done by defining a connectivity matrix for the whole network and setting up the appropriate continuity condition at each node.

Eriksson [5] developed and investigated a set of exhaust temperature models suitable for the design and analysis of engine control systems. These models are lumped parameter heat transfer models that fall within the category of mean value engine models. The objective was to describe the temperature drops in pipe sections in the exhaust system in order to calculate the exit temperature. Fu et al. [6] used the same model to study 1D heat transfer in engine exhaust systems. Both models were driven by applying energy conservation over the pipe element neglecting the Thomson joule effects and also the term related to the heat gained from friction. No implicit coupling with the hydraulic model was performed in these two models.

1.3. Application of thermal models in pipes

This section covers some of the literature related to the effect of considering thermal modeling in exhaust pipes and gas pipeline networks. According to Kandylas [7], the work on studying the heat transfer in exhaust pipes is not recent (he referred to some work between 1977 and 1987). However, more interest in this field started to emerge in the 2000s in conjunction with the development of after treatment devices. Thermal models are important at this point to understand and optimize the behavior of the heat transfer processes in these devices such as the warm up in the catalytic converter or the regeneration process in diesel particulate filters. In the same study mentioned earlier by Modisette [3], the isothermal assumption, various types of transient and steady-state fluid thermal models, and coupled transient fluid thermal models were compared for gas and liquid pipelines. One of the author's interesting conclusions was that it made little difference whether the energy equation was solved at the same time as the mass and momentum equations, or in alternating steps. In order to get this agreement, it is necessary to include in the hydraulic model terms accounting for the rate of change of temperature with time. It can be deduced that using the same approach to obtain a steady state solution, will provide the same convenient results as well and the variation of the temperature with time can be neglected in this case.

Osiadacz et al. [8] presented a comparison between using isothermal and non-isothermal models for hydraulic calculations in gas pipeline systems. The results of this comparison showed a significant difference in the pressure distribution along the pipeline between isothermal and non-isothermal model. This error also increased at higher gas flow rates. The author suggested that the problem of selecting the suitable thermal model depends mainly on the complexity and the structure of the network, although certain measures to evaluate these factors were not mentioned.

Chaczykowski [9] studied the effect of using a non-isothermal steady state thermal model on the accuracy of the overall pipe flow model by comparing it to the transient non-isothermal thermal model. These thermal dynamic effects are usually important in case of large flow fluctuations caused by devices such as valves, compressors and pressure regulators. The result of this comparison showed that the accuracy of the solution can be significantly improved using the transient model instead of the steady-state heat model. This paper also discussed the effect of some factors usually not considered in steady state simplified models including potential and kinetic energy changes and Joule–Thomson effect, thermal effects due to friction, and heat transfer to/from the surroundings of the pipeline.

In parallel to the above efforts, acousticians studied the effect of axial temperature gradients inside a uniform hard duct on the acoustic propagation. Cummings [10] studied the sound propagation inside hard-walled ducts where both mean axial flow and temperature gradients are present. He attempted to achieve an “engineering solution”. Even though strong radial gradients in time-averaged quantities such as velocity and temperature must naturally exist, his past success of one-dimensional treatments in this sort of situation has encouraged him to take account only of axial gradients, which simplifies the analysis enormously.

Peat [11] derived self-consistent expressions for the four-pole parameters of a uniform duct with a linear temperature gradient for the general case of a superimposed mean flow. He performed some experimental measurements which validated the approximations he made and indicated little practical benefit in detailed modeling of temperature variations inside a certain element. It was enough to use the axial temperature within these elements.