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Heat transfer analysis of a circular pipe heated internally with a cyclic moving heat source

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ABSTRACT

Moving heat source (MHS) problems are widely encountered in many engineering applications. In this paper, transient heat transfer of a circular pipe subjected to an internal cyclic expanding heat source is investigated. The right boundary of the heat source moves from its original position to the end of the circular pipe in a few milliseconds, during which the inner wall is under forced convective heating and then the pipe is under natural cooling for a few seconds. This is called a cycle. A finite volume method is used to analyze the transient heat transfer of the pipe under this cyclic thermal loading. Temperature responses, heat flux responses and temperature distributions are presented to show the thermal characteristics of such a pipe. Results show that the inner wall is under intense thermal impact and a large temperature gradient occurs in the region near the inner wall. The effect of exterior water cooling method on the heat transfer in the pipe is investigated. Predictions show that this method can reduce the growth trend of the peak temperature of the inner wall and take much heat away that stored in the pipe.

1. Introduction

Heat transfer problems of solids (plates, cuboids, cylinders) subjected to a moving heat source (MHS) are widely encountered in many engineering applications, such as manufacturing processes (grinding, welding, cutting and so on), frictional devices, solid propellant rocket motors, gun barrels, engine exhaust valves, etc. Yapıcı et al. [1] conducted a detailed literature research of the heat transfer problems in manufacturing processes, in which the heat source usually moves at a low velocity (such as several centimeters per second), and the maximum temperature may occurs at the edge of the MHS. This paper considers such a problem that a circular pipe is subjected to an internally expanding convective boundary conditions. The right edge of the heat source is accelerating during this heating period and its velocity may reaches 1000 m/s eventually. This heating period lasts only a few milliseconds, followed by a cooling period of several seconds. The maximum heat transfer may reach about 1 MJ/m^2. Unlike the manufacturing processes, the maximum temperature will occur near the original position of the heat source and a large temperature gradient will occur at the inner wall due to the high gas temperature and convective coefficient. Under the cyclic conditions, the inner wall will undergo periodic heating and cooling, which will induce large cyclic thermal stress leading to the failure of the pipe. A precise temperature evaluation is very important for the design of this pipe.

MHS problems have always been of much concern to many researchers. Ling and Yang [2] presented a solution for the temperature distribution in a semi-infinite solid excited by a fast moving arbitrarily distributed heat source, which was represented by Fourier series. Modest and Abakians [3] expanded the body of conduction solutions to include the cases of continuous wave and pulsed laser irradiation and developed a simple conduction model that accounts for the conduction losses caused by melting and evaporation. Nguyen et al. [4] derived analytical solutions for the transient temperature field of semi-infinite body subjected to three dimensional (3D) power density moving heat sources. Hou and Komanduri [5] presented analytical solutions for stationary/moving plane heat sources of various shapes and heat intensity distributions. The analysis could be used to determine the temperature distribution not only at the surface but also with respective to the depth. Laraqi et al. [6] proposed some exact analytical solutions of the temperature distribution and the thermal resistance on semi-infinite bodies for three geometric configurations, which correspond to several types of contact problems. Ali and Zhang [7] established a unified framework for solving heat conduction

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problems with an instantaneous point MHS using the relativistic moving heat source model. Araya and Gutierrez [8]obtained an analytical solution of the transient temperature distribution in a finite solid when heated by a moving heat source by using the method of separation of variables. Two different heat source distributions were used: a Gaussian distribution and a spatially uniform plane heat source. Kidawa-Kukla [9] obtained an exact analytical solution of the temperature distribution in a rectangular plate subjected to a moving heat source, which moved along an elliptical trajectory by applying the Green's function method. Talati and Jalalifar [10] presented an analytical solution for a disk brake system by using Green's function method and various parameters were taken into account. Aderghal et al. [11] developed a general analytical solution for the temperature rise at any point due to a stationary or moving band heat source with uniform heat intensity distributions. A numerical solution was also adopted to study the influence of cooling on the evolution of surface temperature.

Developments in computer technology make it convenient to use numerical simulations nowadays. Numerical simulations have been used to investigate many problems with moving heat source, such as a disk brake [12–15], manufacturing processes [16–19], functionally graded circular pipe [20,21]. Adamowicz and Grzes [12] evaluated the influence of convective cooling on the thermal behavior of a disc brake system during repetitive braking processes by using a fully 3D finite element model. Belhocine and Bouchetara [13–15] used the computer code ANSYS to analyze the thermal behavior of the full and ventilated brake disc of vehicles. Hamraoui [16] used the finite volume method to investigate the thermal behavior of rollers during the rolling processes. Kim and Zhang [17], Majumdar et al. [18] and Moulik et al. [19] used the finite element method (FEM) to solve the heat transfer problems of laser cutting, cutting processes and grinding processes, respectively. Malekzadeh et al. [20,21] used FEM to solve the heat transfer of functionally graded cylinders and functionally graded plates subjected to moving heat source. Thermal stresses in a thick walled cylinder or circular pipe subjected to a periodic moving heat source heated internally or externally were also investigated by some researchers [1,22].

The purpose of this study is to analyze the heat transfer of a circular pipe subjected to internally cyclic expanding convective boundary conditions, which are both functions of time and location. This problem is encountered in many launching systems (such as a rocket or gun), in which the barrel suffers a lot from the severe thermal loading. Results of temperature responses, heat flux and temperature distributions are presented. In addition, the method of an exterior water cooling is taken into account. Its effects on the temperature responses, heat transfer and temperature gradient are analyzed in detail.

2. Physical model

2.1. Problem description

In launching systems, the projectile is initially positioned at a fixed place in the tube (circular pipe). When the propellant grains in the chamber are ignited, they generate high temperature and high pressure gases that drives the projectile to move forward. During this period, the propellant gases expands with the moving of the projectile. Because they are very high temperature and have a large velocity, the convective heat transfer between the gas and the pipe wall is very large. The pipe is mainly heated up by this kind of expanding convective boundary condition.

In this work, we use the finite volume method (FVM) to calculate the temperature response of such a pipe, as seen in Fig. 1. The right boundary of the heat source represents a moving piston

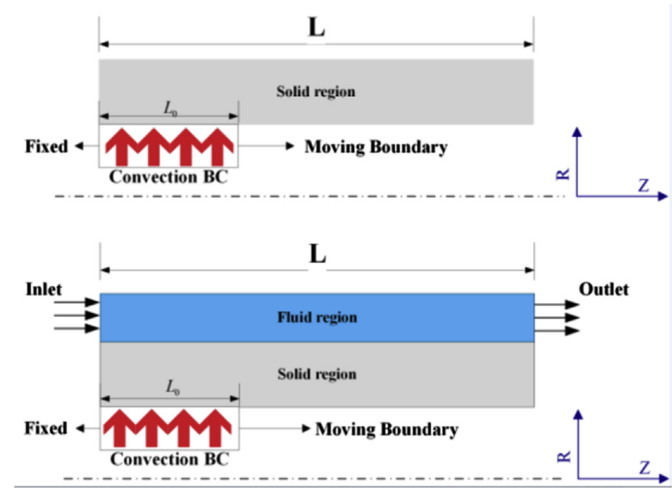

Fig. 1. Geometry of a circular pipe heated internally with an expanding heat source without cooling water (top figure) and with cooling water (bottom figure).

or a projectile moves from $z = L_0$ at the beginning to the right-hand end of the cylinder and this process lasts about 15 ms. After exist of the projectile, the inner wall and outer wall (bottom and top in Fig. 1) of the cylinder cools under natural conditions. The heating period and the cooling period is called a cycle (round) and the period is set to be about 6 s. During the continuous firings, before the pipe cools thoroughly to the ambient temperature, another projectile is launched. Due to the presence of the residual temperature, the temperature of the pipe accumulates as long as the cycles continue. Consequently, the maximum temperature of the inner wall continues rise and this may lead to the self-ignite of the propellant, which is a dangerous treat. Additionally, the erosion of the inner wall become severer when the maximum temperature is higher. The length of the cylinder is 8.62 m, L_0 is 1.271 m, the thickness of the solid region is 5 cm and the width of the water channel is 6 mm. It is to be noted that the scale of two coordinates in Fig. 1 is different to show the model better. The expanding heat source is assumed to be axisymmetric, and thus the axisymmetric model is adopted in this paper to save computational cost.

2.2. Governing equations

Here we give the governing equations of the fluid region and solid region.

Continuity Equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

Momentum Equation:

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right) \tag{2}$$