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Heat transfer and thermal stresses in a circular tube with a non-uniform heat flux

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ABSTRACT

This paper presents a thermal analysis of thin-wall pipes under non-uniform heat flux in the circumferential direction, with a turbulent flow in statistically stationary state inside. The temperature distribution in the solid and in the fluid is obtained using an spectral method that solves the conjugate heat transfer problem. Special attention is paid to the inner wall fluid temperatures and the thermal stresses on the solid, that are compared to predictions based on 1D models in which the circumferential heat transfer is neglected. The comparison shows that, even if at sufficiently large Biot numbers ($Bi \gtrsim 0.3$) the 1D model gives a reasonable prediction of the inner wall fluid temperatures (less than 5% of error), the 1D model for the thermal stresses is only appropriate for very large Biot numbers ($Bi \gtrsim 10$), giving qualitatively wrong results for Biot numbers below 0.3.

1. Introduction

Cumulative fatigue damage plays a key role in life prediction of tubular heat exchangers subjected to time varying heat fluxes. To estimate the tube thermal fatigue, the maximum thermal stress must be obtained for different operating cycles [1]. Therefore, the effect that the operating conditions and fluid properties have on the tube temperature profiles is of paramount importance from an engineering point of view.

There are many circumstances under which the tube thermal stress determination is straightforward. Such is the case of pipes under uniform heat flux, where the mean temperatures of the fluid and pipe wall vary linearly along the axial direction [2], while the temperature in a section of the pipe is a function of only the radial direction. In such situations the thermal stress problem becomes a one-dimensional problem, and the effective stress can be obtained knowing the heat flux and the thermo-mechanical properties of the pipe [3].

On the other hand, there are applications where uniformity is not found. Concentrating solar power is a good example of such applications. In solar central receivers, for example, the front-tube section must withstand high heat flux (around 1 MW/m^2) whereas the rear-tube section is almost adiabatic, resulting in a circumferentially-varying heat flux on the outer wall of the pipe. That heat flux is transferred to the molten salt flowing inside the tube, resulting as well in a circumferentially-varying heat flux on the inner wall of the pipe. This asymmetry precludes, in principle, the use of one-dimensional solutions to obtain the peak thermal stress.

Similar working conditions can be found in other industrial applications, like parabolic trough collectors, space-vehicle heat-exchangers or in the cooling system of nuclear reactors. In all these cases, the non-uniform heat fluxes produce radial and circumferential temperature gradients in the tube walls, which result in thermal stresses on the solid and circumferential variations of the fluid temperature at the wall. Both, thermal stresses and inner wall fluid temperature, are extremely important from an engineering point of view, since the former can produce mechanical failure of the pipe and the latter controls the chemical degradation of the heat transfer fluid [4].

The prediction of heat transfer for non-uniform configurations has been the subject of many research studies in the past, using analytical methods, experiments and numerical simulations. First Reynolds [5] and later Rapier [6] studied the case of a thermally developed flow with circumferential varying heat flux from an analytical point of view. They assumed a fully developed turbulent flow in the pipe, and prescribed a heat flux that was expressed as a sine or cosine series with zero mean value. The resulting temperature profiles in the fluid were obtained as a series of sines or cosines, whose coefficients vary with the Reynolds and Prandtl number of the flow. Comparing theinner wall fluid temperatures predicted by Reynolds [5] for a sinusoidal heating with the inner wall fluid

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temperatures obtained from applying the Dittus and Boetter correlation yields a difference on the maximuminner wall fluid temperatures of about 50% for the typical working conditions of concentrating solar power receivers (Reynolds number $Re = 30{,}000$, Prandtl number $Pr = 10$).

Although Reynolds [5] and Rapier [6] did not take into account the fluid-wall interaction, the thermal interaction inside ducts has been the interest of many other investigations. Several aspects of this problem have been studied in the context of laminar flows, like the effect of unsteadiness in the heat flux [7–9], or the effect of spatial inhomogeneity in the axial direction [10,11]).

Painstaking experimental studies have also been carried out in the past. Black and Sparrow [12] investigated the local and average heat transfer coefficients of an air flow through a tube with circumferential varying wall heat flux. More recently, Yang and co-workers [13] measured the heat transfer performance of spiral tubes with molten salts as heat transfer fluid. The results from these investigations also show differences between the experimental values of the Nusselt number and the correlations generally used in literature.

Other researchers have tried to tackle the problem of non-uniform heating in turbulent flows from a numerical point of view, in more or less idealized configurations (fully developed turbulent flow, relatively low Reynolds and Prandtl numbers, constant fluid properties, etc.). Weingand and Gassner [14] analyzed the conjugate heat transfer problem showing that axial heat conduction effects in the fluid are important for low Peclet numbers and that these effects might drastically influence the heat transfer behavior for short heating sections even at higher Peclet numbers. Some studies focus on the evaluation of the eddy-diffusivity associated to the non-uniformity of the heat flux [15,16]. Other studies are concerned with the evaluation of thermal field and thermal stresses along the solid wall [17].

There are also numerical studies of more applied cases, typically using Reynolds-Averaged Navier Stokes simulations to solve the heat transfer in the fluid. For instance, Flores and co-workers [18] report an analysis of thermal stresses on the collector of a solar thermal plant for different configurations, and Rodríguez-Sánchez et al. [19] compares two simplified 2D models using a RANS calculation with a commercial software for the evaluation of inner wall fluid temperatures and thermal stresses on a solar external receiver. In the same vein, Kim et al. [20] proposed a correlation for the convection losses in tower solar receivers using CFD simulations. Wang and co-workers [21] analyzed the conjugate heat transfer problem in a parabolic trough collector showing that asymmetric heat flux has a significant influence on the local heat transfer process.

In view of the above results, it is clear that the prediction of the thermal stress history for a tubular heat exchanger heated non-uniformly is a difficult problem. While simulations solving the conjugate heat transfer problem provide accurate results, they typically require additional simplifications regarding flow properties, geometries, etc. On the other hand, experimental measurement can be extremely expensive and time consuming. However, the engineering approaches used to determine theinner wall fluid temperatures and thermal stresses are usually based on empirical correlations derived from uniform heat flux conditions. The rationale for that simplification is that locally the conditions are uniform, with stronger temperature gradients in the radial direction than in the axial or circumferential directions. For instance,inner wall fluid temperatures are usually estimated using Nusselt number empirical correlations (e.g., Kolb [22] uses the Gnielinski correlation and Jianfeng and co-workers [23] use the Dittus and Boelter correlation). Thermal stresses are customarily obtained using formulas derived for a circular tube with a radial temperature distribution (i.a, uniform heat flux in the circumferential direction),which can be found in specialized books [24–26].

In principle, the parameter that controls whether a local approach is valid is the Biot number: the ratio between the characteristic heat flux in the radial direction and the characteristic heat flux in the circumferential direction. If we consider the conjugate heat transfer problem (solid + fluid), the heat fluxes in the radial direction (r) are controlled by the heat transfer in the solid–fluid boundary, and the heat fluxes in the circumferential direction (θ) by the conductivity of the solid. The definition of the Biot number is then

$$Bi = \frac{he}{\kappa_s}, \tag{1}$$

where h is the convective heat transfer coefficient between the fluid and the solid, e is the thickness of the tube wall and κ_s is the conductivity of the solid. For large values of Bi, the radial heat flux is dominant, and one can expect the correlations and methods based on uniform (radial) heat fluxes to be applicable locally. However, when the Bi is small these methods should be expected to fail.

The objective of the present work is to establish the range of Biot numbers where the local approach is applicable in pipes with non-uniform heating in the circumferential direction. When the local approach is applicable, the solution of the conjugate heat transfer problem can be avoided, thereby simplifying the stress analysis. To achieve this, the conjugate heat transfer problem for a circular pipe with a circumferentially varying heat flux and a fully developed turbulent flow inside is solved using a simple eddy diffusivity model and constant fluid properties.

Different fluid velocities, tube diameter and thickness have been studied, in order to analyze a range of Biot numbers spanning two orders of magnitude. Particular attention is paid to the effect of the Biot number on the inner wall fluidtemperature and thermal stresses, and to our ability to estimate them using simple 1D models.

To some extent, the present numerical work can be considered as a continuation of previous works that only considered the heat transfer in the fluid part [5,6,27]. Here we add also the heat transfer problem on the solid part.

The paper is structured as follows. First, Section 2 describes the formulation of the conjugate heat transfer problem, and the details of the numerical solver. Section 3 presents the results obtained in the calculations, discussing the inner wall fluid temperature (Section 3.2) and the thermal stresses on the solid (Section 3.3) in terms of the Biot number. Finally, conclusions are offered in Section 4.

2. Physical, mathematical and numerical model

2.1. Physical model

We consider the conjugate heat transfer problem of a circular pipe subject to homogeneous heating along the axial/streamwise direction (x) and non-homogeneous heating in the circumferential direction (θ). The inner radius (diameter) of the pipe is denoted $R_i(D_i)$, while the outer radius (diameter) is denoted $R_o(D_o)$. The wall-thickness is $e = R_o - R_i$, and r is the radial coordinate.

A sinusoidal heat flux is imposed on one half of the wall of the pipe, while the other half is considered adiabatic, resulting in a heat flux on the outer surface

$$q_o(\theta) = \begin{cases} q_{max} \sin\theta & \text{if} \quad 0 \leqslant \theta \leqslant \pi \\ 0 & \text{if} \quad \theta > \pi \end{cases} \tag{2}$$