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Numerical study on conjugate heat transfer in laminar fully developed flow with temperature dependent thermal properties through an externally heated SiC/SiC composite pipe and thermally induced stress

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Abstract

This study presents numerical solutions of conjugate heat transfer in laminar, fully developed flow through an externally heated pipe and the thermally induced stress under high temperature conditions. For this purpose, a SiC/SiC composite and liquid metals (lithium and sodium) were considered as pipe material and fluid, respectively. Various flow cases were considered as: the lithium and sodium flows with constant thermal properties, CTPs, and with temperature dependent thermal properties, TTPs. The calculations were performed individually for a wide range of thermal conductivity of the solid ($k_s = 10$–100 W/m K stepped by 10 W/m K) and various mean pipe inlet velocities ($U_m = 0.01$–0.02 m/s stepped by 0.002 m/s) under both steady state and transient conditions. In order to keep the maximum relative temperature of the solid within the interval, $\theta_s = 190$–200 K, also the temperature controlled heating case was performed. Furthermore, a computer program, applying the SIMPSON integration method to the obtained temperature distributions from the heat transfer calculations, has been developed to calculate numerically the thermal stress distributions. The temperature difference ratios, TDRs, which are the ratios of the difference of temperatures at the same point in both flow cases to the relative temperature at that point in the temperature dependent thermal property cases, in the lithium flow case are lower than those in the sodium flow case, and the averages of the TDRs in the solid, fluid and outlet regions are about 2% and 6–7% in the lithium and sodium flow cases, respectively. Although the increase of U_m substantially affects the relative temperatures, it does not affect very much the effective thermal stress. The maximum effective thermal stress ratios decrease exponentially with the increase of k_s. As the radial distance increases, the effective thermal stress ratios, having maximum values at the inner radius ($r/D = 0.4$), reduce to minimum values at almost

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$r/D = 0.445$ and then increase. The results of this study would serve to determine the temperature distributions and the thermally induced stresses in similar pipe flow applications.

Keywords: Conjugate heat transfer; Pipe flow; Fully developed laminar flow; Thermal stress; Temperature controlled heating; Computational fluid dynamics

1. Introduction

Heat transfer under laminar flow conditions in pipes is encountered in a variety of engineering applications. One of these applications is the heat exchangers in which conduction occurs in a solid tube and convection occurs in the fluid flowing within the outer surface. The term conjugate heat transfer is used to describe processes that involve variations of temperature within solids and fluids due to thermal interaction between the solids and fluids. Therefore, conduction and convection heat transfers must be simultaneously analyzed. In problems referred to as conjugated, because the thermal boundary conditions along the solid–fluid interface are not known a priori, the energy equations should be solved under the conditions of continuity in temperature and/or heat flux. In addition, in this type of heat transfer analysis, the two chief obstacles to a workable theory are geometry and viscosity. The general theory of fluid motion is too difficult to enable the user to attack arbitrary geometric configurations. It can be possible to apply merely numerical techniques to arbitrary geometries. The second obstacle to theory is the action of viscosity, which can be neglected only in certain idealized flows. Therefore, a suitable numerical method and/or computational fluid dynamics (CFD) code is frequently used to solve the governing equations in this field. The CFD code is the process by which fluid flow can be predicted through arbitrary geometries, giving such information as flow speed, pressures, residence times, flow patterns etc. The main advantage of this approach is in its potential for reducing the extent and number of experiments required to describe such types of flow. In the past, many studies on conjugated heat transfer problems in pipe flow have been performed for several geometries and for different boundary conditions. Some of them are given in Refs. [1–14].

Furthermore, non-uniform heating and/or cooling of a uniform material, or uniform heating of non-uniform materials cause thermal stresses that are proportional to the temperature differential and the coefficient of thermal expansion of the material. Some of these thermal effects include thermal stress, strain and deformation. Therefore, thermally induced stresses are taken into consideration as important phenomena in many engineering applications. A thermal analysis is first conducted, providing the temperature distribution throughout the structure or product either at a steady state condition or as a function of time. The stress analysis is subsequently conducted using the temperatures derived in the thermal analysis plus any additional structural or mechanical forces and constraints imposed on the structure or product. Recently, many researches have numerically solved the thermally induced stress analyses with heat transfer in a pipe for several pipe materials and fluids [15–18].

There is a strong demand to make high performance ceramic matrix composites (CMCs) for advanced energy systems such as nuclear fusion reactors and advanced gas turbine engines. Among them, the silicon carbide composite (SiC/SiC), which is also known as a very low