

Modeling of turbulent buoyant flow and heat transfer in liquid metals

A. A. MOHAMAD and R. VISKANTA

School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907, U.S.A.

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Abstract—Turbulent natural convection in a cavity filled with low Prandtl number fluids is investigated. The cavity is either heated from below and cooled from above or heated differentially and the other connecting walls are assumed to be thermally insulated. Direct numerical simulations, and two- and three-dimensional low Reynolds number $k-\epsilon$ turbulence models are used. It is shown that the turbulent Prandtl number equal to one or slightly greater than one produces useful results, regardless of the value of molecular Prandtl number. A correlation is suggested for the Nusselt number as a function of $Ra Pr$ (Boussinesq number) for natural convection in a differentially heated cavity. The flow becomes turbulent for $Ra Pr > 4.8 \times 10^7$.

INTRODUCTION

NATURAL CONVECTION of liquid metals has been a subject of study by nuclear reactor engineers and metallurgists. Liquid metals are excellent heat transfer media. During shut down of a liquid metal cooled nuclear reactor, heat transfer from the reactor core to the liquid metal coolant takes place by natural convection. In severe nuclear reactor accidents heat transfer in the molten core debris takes place by buoyancy driven convection. Natural convection in low Prandtl number fluids has undesirable effects in crystal growth in the Bridgman bath or Chochrawski apparatus, because the migration of the impurities by natural convection affects the quality of the crystal. Also, oscillation of temperature due to instability of the buoyant flow of liquid metals induces nonuniform cooling at the solidification front. In casting and material processing it is very important to keep the melt at a uniform temperature during the solidification in order to decrease the thermal stresses. Hence, understanding of the flow and heat transfer in liquid metals is essential in many processes including those mentioned above. Since the kinematic viscosity of a liquid metal is very small and the liquid metal containers can be large, the flow is characterized as turbulent. Hence, it is very difficult to maintain laminar flow conditions in practical systems.

Experimentation with liquid metals is difficult, and very few experiments with buoyancy driven flow have been performed. Transport phenomena in liquid metal flows are not as fully understood in comparison with the flow and heat transfer in ordinary liquids such as air and water. Experimental natural convection heat transfer data have been correlated as functions of the Grashof or Rayleigh numbers. The data are limited to laminar flow, and very few data are available for the turbulent flow regime [1-5].

Natural convection in a differentially heated cavity has been studied [6-9]. Results showed that the buoy-

ant flow in a differentially heated cavity can differ in essential ways from the flow of ordinary liquids [8, 9]. Thermal diffusion in a liquid metal is important, and the hydrodynamic boundary layer is very thick for buoyancy driven flows; while for ordinary fluids the hydrodynamic boundary layers are thin, and the maximum velocity of ascending and descending flow occurs near the boundaries. Another feature of the buoyant flow in a liquid metal is the formation of weak secondary circulations in the corners of the cavity. Flow separation takes place at the corners, because the peaks of ascending and descending velocities occur far away from the boundaries, leading to formation of secondary circulations in these regions. Also, the core of the cavity may contain several secondary circulations rotating inside the main circulation. As discussed elsewhere [8, 10], the first evolution process of such weak secondary circulation is in the upper right-hand corner (near the cold wall) of the cavity and by skew symmetry in the lower left-hand corner (near the hot wall). The reason that these corners are more unstable than the remaining ones is that the hot (low density) fluid is below the cold (high density) fluid, which produces unstable flows in these corners.

The process of transition to turbulent flow is discussed by Mohamad and Viskanta [10]. The turbulent buoyant flow of low Prandtl number fluids has not been addressed and is the subject of the present work. Currently, the attention of a turbulent modeler has been focused on the low Reynolds number (LRN) $k-\epsilon$ turbulence model and the Reynolds stress transport term-by-term modeling, and to some extent on large scale and direct numerical modeling [11]. The latter modeling process requires extensive computer resources and presently is not practical for more routine engineering design calculations. The term-by-term Reynolds stress approach requires tuning of the empirical model constants and requires greater computer time resources compared to the $k-\epsilon$ turbulence

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