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Investigation on reverse flow phenomenon in U-tubes under the conditions of ship maneuver

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A B S T R A C T

For the natural circulation, it is shown that the reverse flow phenomenon may occur in the vertically inverted U-tube steam generators (UTSG), which has some negative influences on the passive safety of nuclear power plant (NPP). However, related researches on the reverse flow in UTSG in marine NPP are relatively few. In present work, the characteristics of single phase reverse flow in the U-tubes under the conditions of ship maneuver are investigated using the computational fluid dynamics (CFD) method. The effects of swerving, raising and sinking of ship on the reverse flow phenomenon in the U-tubes are analyzed. The results show that these movements will significantly change the hydrodynamic characteristics of fluid flow in U-tubes. The acceleration in the portside direction of ship will reduce the possibility of reverse flow, whereas the acceleration in the starboard direction will increase that. On the other hand, the possibility of reverse flow will be decreased or increased when ships accelerate to float up or sink down. The influence of the lateral movement on the reverse flow is greater than that of the upright movement.

1. Introduction

Research on the optimization of flow and heat transfer in channels with different structural shapes or under various operation conditions has been one of the most promising orientations in recent years. Hajmohammadi et al. (2013a) investigated the compound optimization of heat and fluid flow in a new configuration of bend tube, they found that the pressure drop and entropy generation in the bend tube which is consists of three straight pipe segments connected with two 90° bends are considerably reduced when implementing the optimum layout, compared to the standard case of a fully curved section with 180° bend. Using the genetic algorithm, Najafi et al. (2011) provided a set of optimal solutions to investigate the energy and cost optimization of a plate and fin exchanger, several geometric variables had been considered as optimization parameters. Hajmohammadi et al. (2013b) also studied the optimal architecture of heat generating pieces in a fin, they found that the regular configurations of the heat sources commonly used in cooling industry are not optimal, and triangular arrangement is proposed to replace it. Furthermore, the operating conditions such as Reynolds number also can be optimized in a thermal system so that the best exergy utilization and the least irreversibility can be achieved (Ko and Ting, 2006). The above literatures show that the situations of heat and fluid flow should be discriminatively considered under different conditions.

Owning to different weather and hydrology factors, the nuclear-powered ships will shake regularly on the ocean within a period of time. The shaking will bring some significant influences on the flow and heat transfer of coolant in the primary loop. The main reason is that the coolant is subjected to the additional force (Chen et al., 2013). In fact, for the marine nuclear power plant (NPP), there are other factors so called ship maneuver conditions that could cause the additional force, such as the forging ahead, falling back, floating up, sinking down and swerving, etc (Chen et al., 2007).

Gao et al. (1997) researched the additional forces subjected to the coolant under some ocean conditions, for instance, rolling, pitching and heaving. They also showed that the additional forces would change the flow and heat transfer situations in the primary coolant. In other words, the flow and heat transfer of coolant in the NPP under the ocean conditions will be different from that under the land conditions. According to existing literatures, the single phase natural circulation flow in the vertically inverted U-tube steam generators (UTSG) can be unstable and the reverse flow may occur inside some U-tubes (Kukita et al., 1988; Sanders, 1988; Jeong et al., 2004). The natural circulation ability plays an

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important role in the passive safety performance of NPP. However, the existence of reverse flow in the UTSG will enhance the flow resistance and weaken the performance of heat transfer, which will also have a negative influence on the natural circulation. So, the investigation of reverse flow in the UTSG has a great practical significance. The differences of reverse flow between the ocean and land conditions had been analyzed by Hao et al. (2013a,b, 2014b) and Chu et al. (2014). The conclusions showed that the critical pressure drop of U-tube will fluctuate with the time when this phenomenon occurs under ocean conditions, and the primary cause is also the additional force produced by movement of ship.

In this paper, the reverse flow phenomenon in U-tubes under the conditions of ship maneuver is researched based on the CFD method. The appropriate U-tube model for the ship maneuver is established, and the additional forces in the different directions are considered using the User's Defined Function (UDF) of FLUENT code. The different ship movements will generate various additional forces on the coolant, which is added in the solution process of momentum equations.

2. Theoretical models

2.1. Maneuver conditions

It is assumed that the U-tube is located in the Cartesian coordinates, as shown in Fig. 1. Based on the theory of ship motion, when the ships forge ahead with a constant positive acceleration or fall back with a constant negative acceleration, the coolant inside the U-tube in Fig. 1 will be subjected to a constant additional force along with positive *y*-axis. Analogously, if the ships float up with a constant positive acceleration or sink down with a constant negative acceleration, the additional force will be along with negative *z*-axis (Chen et al., 2013).

The additional forces along with *y*-axis are always perpendicular to the flow direction and will be offset by the counterforces of the U-tube wall, so its influence on the flow and heat transfer of coolant can be neglected (Yan et al., 2010). The constant additional accelerations along with *x* and *z* axes can be added in the momentum equations with the help of UDF provided by FLUENT code. Then the movements of U-tubes in *x* and *y* directions are modeled successfully. By means of reducing the inlet mass flux in the U-tubes, the transition from the forced circulation to natural circulation is simulated, and the curves of pressure drop between the U-tube inlet and outlet versus mass flow rate are obtained. As a result, the effects of the ship and/or U-tube movement on the reverse flow can be analyzed, theoretically. It's important to note that the practical motion directions of U-tubes are much more complex, but the acceleration can be decomposed in the Cartesian coordinates system. According to the calculation results of this paper, the characteristics of reverse flow in the UTSG under the ship maneuver conditions can be estimated rapidly and effectively.

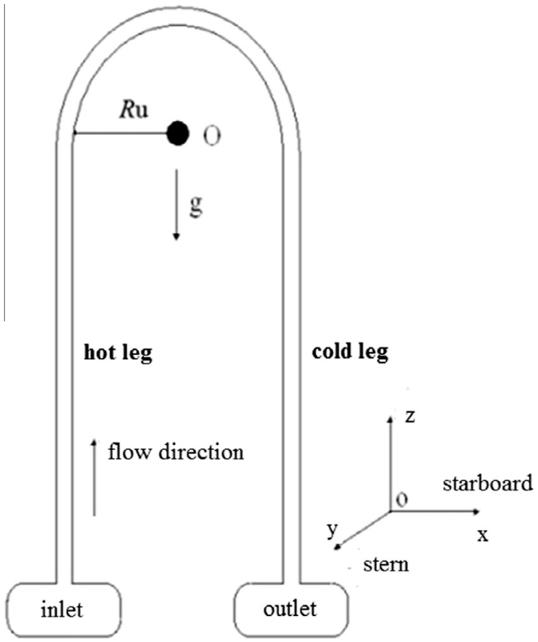

Fig. 1. Schematic of U-tube under ship maneuver.

2.2. Turbulent model and boundary conditions

It is well known that the most common turbulent models in FLUENT code are k–ε, k–ω and RSM (Reynolds stress model) (Fluent Inc, 2009). The existing literatures have shown that the realizable k–ε model and RSM can provide a perfect performance for the flow with the complex secondary flow feature. However the RSM need much more calculation source and time, so the realizable k–ε model is introduced (Hao et al., 2014a). To obtain the accurate results, the second order upwind scheme is adopted as the spatial discretization format. The boundary conditions of U-tubes are the inlet mass-flow and outlet pressure. It is assumed that the U-tube wall temperature is constant and equal to the saturated temperature corresponding to the secondary operation pressure (Hao et al., 2014a). The structured mesh is used because of its superiority in the calculation speed. The enhanced wall treatment is adopted in the case, and it should be ensured that the *y* plus for the first mesh to the wall is less than 1. It is assumed that the physical property parameters of fluid in the U-tubes, which include density, specific heat capacity, dynamic viscosity and thermal conductivity, are just the linear functions of temperature (Hao et al., 2014a,b). These parameters can be expressed as follows, respectively (Hao et al., 2014a):

$$\rho(T) = 857.4124 \times [1 - 0.00167 \times (T - 487)] \quad (1)$$

$$c_p(T) = 4494.5 \times [1 + 0.002 \times (T - 487)] \quad (2)$$

$$\mu(T) = 1.28 \times 10^4 \times [1 - 0.003844 \times (T - 487)] \quad (3)$$

$$\lambda(T) = 0.66517 \times [1 - 0.001592 \times (T - 487)] \quad (4)$$

where ρ, c_{p}, μ, and λ are the density, specific heat capacity, dynamic viscosity and thermal conductivity of the fluid, respectively. T is the temperature.

After the analysis of mesh sensitivity, the amount of the most suitable mesh for calculation reaches to 310,500.

3. Calculation results and analysis

The total pressure drop between the inlet and outlet of U-tube mainly includes the flow resistance and gravity pressure drop. Thereinto, the flow resistance pressure drop Δp_f can be expressed as (Jeong et al., 2004; Hao et al., 2013a,b):

$$\Delta p_f = \frac{\dot{m}^2}{2A^2\bar{\rho}}\left(\frac{fL}{d_0} + \zeta\right) \quad (5)$$

where $\dot{m}$ is the mass flow rate, A is the flow area, f is the frictional resistance coefficient, d_0 is the inner diameter of the U-tube, L is the length of the U-tube, ζ is the local resistance coefficient, $\bar{\rho}$ is the average density.

Based on Boussinesq approximation, the change of density with temperature can be written as (Sanders, 1988):

$$\rho(T) = \rho_0(1 - \beta(T - T_0)) \quad (6)$$