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Research Article

Natural Circulation Characteristics of a Symmetric Loop under Inclined Conditions

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Natural circulation is an important process for primary loops of some marine integrated reactors. The reactor works under inclined conditions when severe accidents happen to the ship. In this paper, to investigate the characteristics of natural circulation, experiments were conducted in a symmetric loop under the inclined angle of 0~45°. A CFD model was also set up to predict the behaviors of the loop beyond the experimental scope. Total circulation flow rate decreases with the increase of inclined angle. Meanwhile one circulation is depressed while the other is enhanced, and accordingly the disparity between the branch circulations arises and increases with the increase of inclined angle. Circulation only takes place in one branch circuit at large inclined angle. Also based on the CFD model, the influences of flow resistance distribution and loop configuration on natural circulation are predicted. The numerical results show that to design the loop with the configuration of big altitude difference and small width, it is favorable to reduce the influence of inclination; however too small loop width will cause severe reduction of circulation ability at large angle inclination.

1. Introduction

Natural circulation is widely used in nuclear systems because of its advantages over the forced flow process, such as the elimination of the pump, improved safety and reliability, and the reduction of maintenance costs [1, 2]. Certain ship-mounted integrated type nuclear power plants also use the natural circulation process for portable desalination [3, 4]. However, the thermohydraulic characteristics of natural circulation in ship-mounted plants are far more complex than land-based plants due to the influence of ship motions such as heaving, rolling, and inclination [5–9] (Figure 1). In the event of incidents such as collision, sinking, or stranding, the reactor will work under inclined conditions. An understanding of natural circulation behavior under different inclined angles is crucial because inclination causes a reduction in the driving force and also a break in the thermohydraulic symmetry of the reactor, where the steam generators annularly surround the core.

Different groups have conducted experimental and numerical studies on specific systems in order to predict the influences of inclination. Iyori [10] used a model of an integrated type marine reactor to investigate the effect of inclination on single-phase natural circulation. Results showed that the temperature distribution from the steam generator at an inclined attitude was primarily dependent on elevation. Kim [11] performed steady-state natural circulation experiments on the test facility of the system-integrated modular advanced reactor (SMART) mounted on leaning equipment for inclination. The experiments investigated asymmetric flow patterns in the upper pressure header, steam generator cassettes, and downcomer during feed water isolation and inclination. Kim [12] also developed a CFD model and investigated the 3D effects of inclination for the same system. Ishida [13] investigated the effects of inclination on thermal-hydraulic behavior of a DRX (deep-sea reactor) using the RETRAN-02/GRAV code. The numerical results showed that ship inclination, even at 60°, induced the core flow to decrease, but the reactor power recovered to initial power levels due to the inherent characteristics of the DRX core. Gao [14] developed a simple mathematical model to

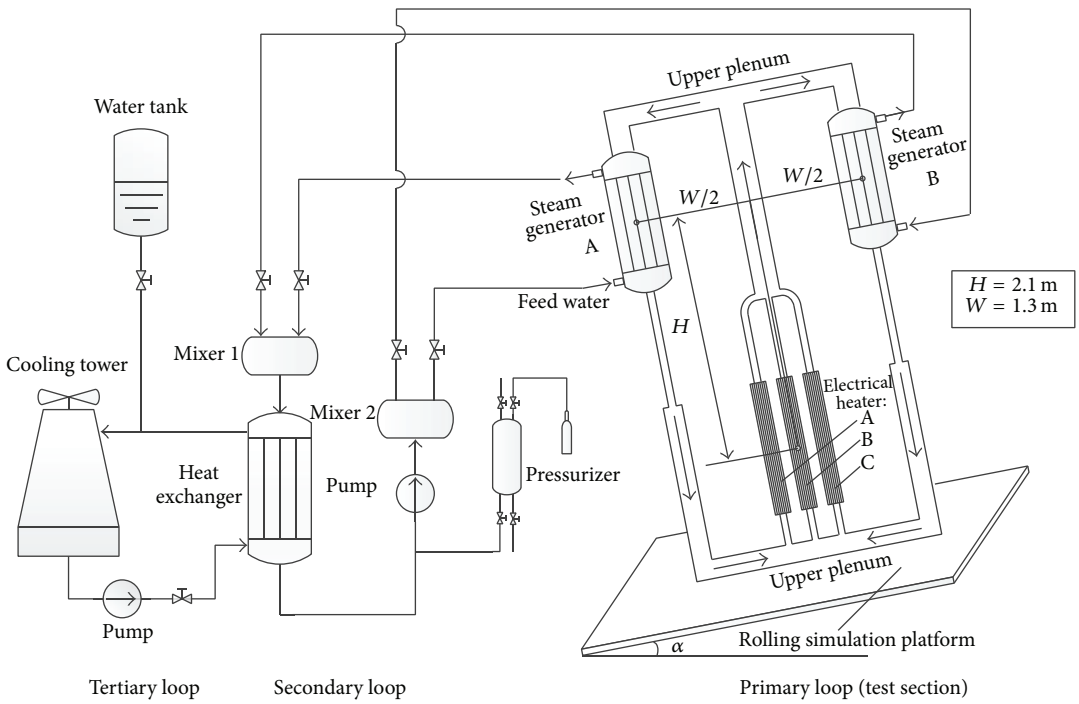

Figure 1: Test apparatus.

predict the circulation characteristics under inclined conditions, but asymmetric effects were not considered in that model. In principle, these results are all restricted to specific systems. The mechanisms of inclination influence are still not comprehensively and quantitatively presented for different systems.

This paper presents research on the natural circulation process in a symmetric two-circuit test loop under inclined conditions. Experiments were conducted under inclined angles of 0~45°. A CFD model was built, based on which the thermodynamics characteristics of natural circulation under inclined angles of 45~90° were also analyzed. Additionally, this paper discusses the variations in overall circulation ability, disparity in branch circulation, and the influence of loop configuration and resistance distribution.

2. Test Apparatus

The test loop consisted of three subloops (Figure 1). The primary loop was the test section, designed as a symmetric two-circuit loop in order to simulate the symmetric characteristics of an actual plant. Three electric heaters (EH), located at the shared part of the two circuits, supplied the heat source. Each heater consisted of 16 $\Phi 10 \times 1$ mm and 1080 mm long stainless steel heating tubes. A direct current was applied to the electric heater during operation, with a voltage up to 75 V and total current of 2000 A. The heat sink was two steam generators (SG) that were symmetrically installed on the upper part of each circuit. Heat generated by EH was finally emitted into the environment through the SG, the secondary loop, and the third loop, in order to establish the energy balance. The effective altitude difference between the heat source and heat sink, H0, was 2100 mm. The distance between the steam generator centers, W, was 1255 mm. The primary loop was installed on a ship motion simulation platform, which inclined about the x-axis and y-axis with maximum angles of 45° and 20°, respectively. The working fluid of the primary loop was demineralized water with a pressure of 4.0 MPa.

The secondary loop consisted of a pump, a heat exchanger, two mixers, and a pressurizer. The coolant for the secondary loop was water driven by a pump rather than natural circulation. The mixer and control valves were used to equally set the coolant temperature and flow rates of the two circuits in order to avoid an unbalanced load. The secondary loop was kept at high pressure (4.0 MPa) to prevent the occurrence of two-phase flow due to the simplicity of the equipment. The pressurizer was filled with high-pressure nitrogen gas in order to adjust and maintain the pressure. The main equipment for the third loop was the cooling tower, through which heat input from the secondary loop was finally emitted into the environment with the coolant circulation.

Ultrasonic flow meters measured the flow of natural circulation at the outlets of each electric heater module and steam generator. The meters had an accuracy 0.5% over the measured flow rate value and did not bring extra resistance to the circulation. The flow rates of the secondary and third loop were measured by orifice-type flow meters. Temperature was measured by thermocouples with an accuracy 1% over the temperature range (according to manufacturer specifications). A total of 36 thermocouples were installed at crucial

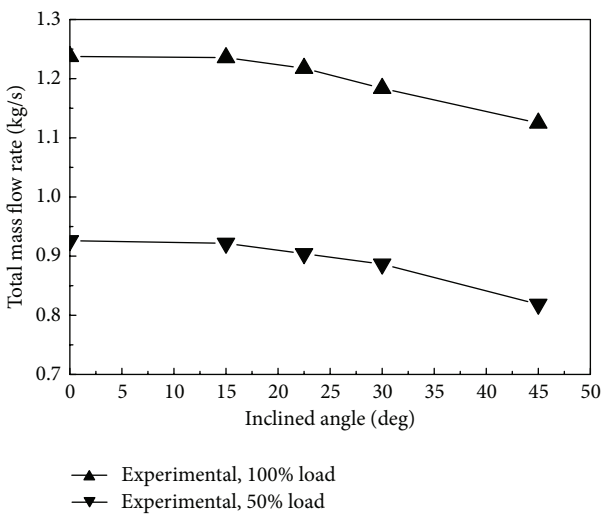

Figure 2: Total mass flow rates under different inclined angle.

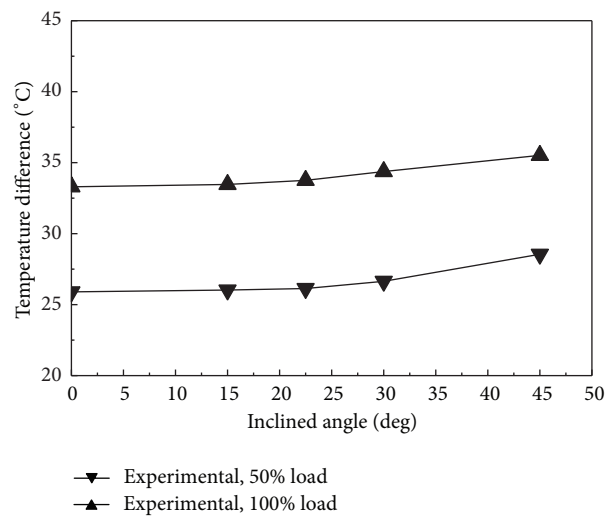

Figure 3: Average temperature differences under different inclined angles.

positions throughout the entire test loop, including the inlets and outlets of EH, SG, and the heat exchanger.

3. Experimental Results

A series of experiments were conducted under inclined angles of 0°, 15°, 22.5°, 30°, and 45°. The maximum inclined angle is 45° because of the restriction of the ship motion simulation platform. Power input from the electric heater controlled the load from 50 to 100%. The flow rates of the secondary and third loop were kept constant during the experiments. The testing was conducted over 2 hours for each inclined angle in order to obtain a steady state.

The volume flow rate of each steam generator outlet was recorded. The total mass flow rate was obtained by multiplying the density computed by the local pressure and temperature. The results showed that an increase in the inclined angle gradually weakened the circulation. An inclined angle of 45° had a mass flow rate approximately 10% less than an inclined angle of 0° (Figure 2). The average temperature difference, $\overline{\Delta T}$, between the hot leg and the cold leg increased as the inclined angle increased (Figure 3). Here $\overline{\Delta T}$ is defined by

$$\overline{\Delta T} = \frac{\Delta T_A \dot{m}_A + \Delta T_B \dot{m}_B}{\dot{m}_A + \dot{m}_B}. \quad (1)$$

Both the flow rate decrease and the temperature difference increase indicated that the circulation ability was inhibited when the inclined angle was increased.

Asymmetry of the steam generator load may cause variations in steam properties and mechanical problems. However, the altitude difference between the cold legs occurs under inclined conditions and leads to a disparity of circulation ability. If the system inclines anticlockwise, the circulation in right branch was always stronger than the left. The flow rate of the right branch increased approximately 2% when $\alpha = 45°$ (compared to $\alpha = 0°$), while the flow rate of the left circuit decreased 26%, as shown in Figure 4.

4. Numerical Model

Numerical analysis of natural circulation in the test section was carried out using CFD package ANSYS FLUENT. The whole meshes were structured and were created using ICEM. A total of 15 interfaces exist in the mesh system, which divided the test section into separated parts. Meshes were created for the parts individually and connected by the interfaces. A boundary layer mesh was generated for all the flow channels. The mesh used for this analysis is shown in Figure 5.

Variation of water properties with temperature was neglected in this analysis. The Boussinesq assumption was employed in calculating the buoyancy force.

The realizable k-ε turbulence model was used in these computations. This scheme is ideal for flows involving rotation, boundary layers under strong adverse pressure gradients, separation, and recirculation. Power law scheme of discretization is used for turbulent kinetic energy and dissipation rate equations. Pressure velocity coupling was done using the SIMPLEC scheme. Momentum equations were discretised using QUICK scheme. Convergence criterion used was $1.0e-3$ for continuity, $1.0e-5$ for velocities, energy, k, and ε.

We adopted porous medium model in simulating the flow and heat transfer in steam generators and electrical heater. In this model the flow resistance is calculated through a coefficient that is an input parameter to FLUENT. Electrical heating power was represented by a source term of the energy equation. Heat transfer in steam generator was calculated by the average heat transfer coefficient and temperature difference between the primary and secondary loop's fluids and added to the energy equation as a source term through UDF (user defined function) programming.

The numerical model was verified through comparing with the experimental results, as shown in Table 1. It can be seen that the numerical results show good agreement with

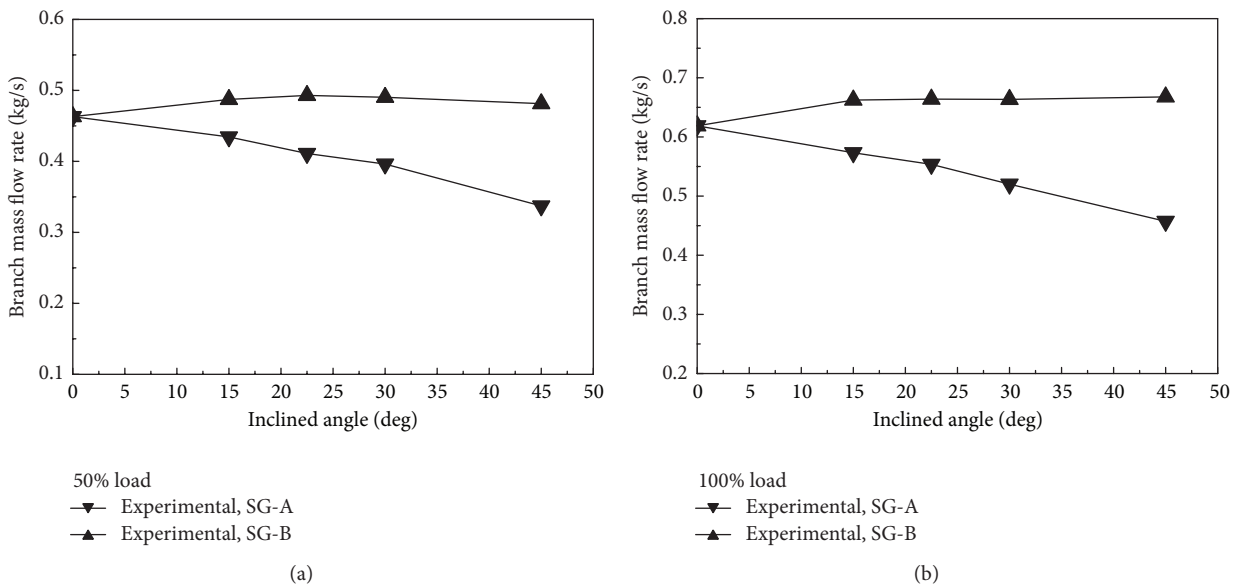

Figure 4: Branch flow rates under different inclined angles—(a) 50% load; (b) 100% load.

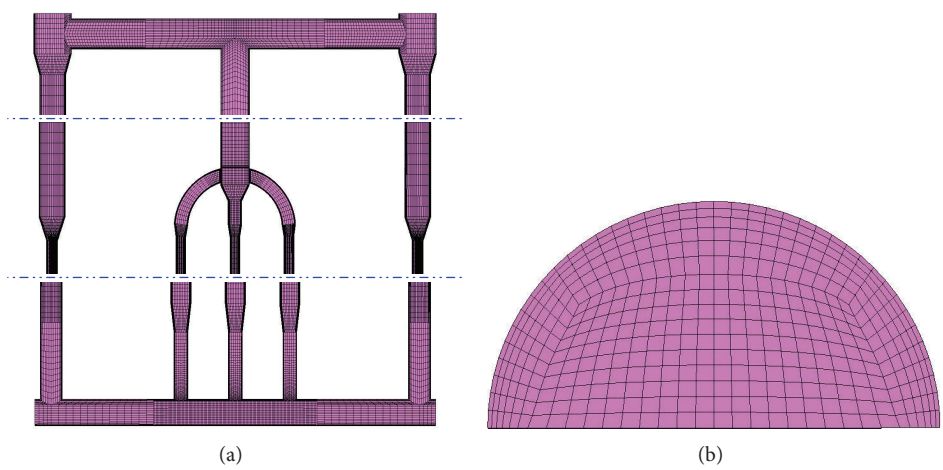

Figure 5: Meshes of test section used in computation: (a) whole test section; (b) cross section of flow channel.

Table 1: Comparison of numerical results and experimental results (noninclination).

Parameters	Experimental	Numerical
Mass flow rate of SG-A	0.61	0.62
Mass flow rate of SG-B	0.62	0.62
Inlet temperature of SG-A	181.10	180.50
Outlet temperature of SG-A	144.63	145.55
Inlet temperature of SG-B	181.71	180.50
Outlet temperature of SG-B	147.38	145.55

the experimental results. The temperature distribution and velocity fields are shown in Figure 6.

5. Numerical Results

5.1. Flow Patterns at Large Inclined Angle (45~90°). The temperature fields and velocity fields were obtained through CFD simulation (Figure 7). In comparing with no-inclination condition, obvious disparities arise under inclined condition. The lower branch circulation was nearly suspended when inclined angle increases to nearly 90°.

Total mass flow rate decreases with the increase of inclined angle continuously (Figure 8), in accordance with the analysis in Section 3. At large inclined angle the circulation mainly occurs in the higher circuit. The effective altitude difference is reaching the minimum value, which is half of the loop width ($W/2$). The total mass flow rate decreases 58% under inclined angle of 90°.

The branch flow of SG-B decreases rapidly when inclined angle increases. When the inclined angle reaches 75° the flow rate of SG-B vanishes (Figure 9). The flow rate of EH-A also decreases which causes the outlet temperature of EH-A to increase (Figure 7). If the inclined angle enlarged to 90°, the temperature of EH-A will exceed the saturated temperature

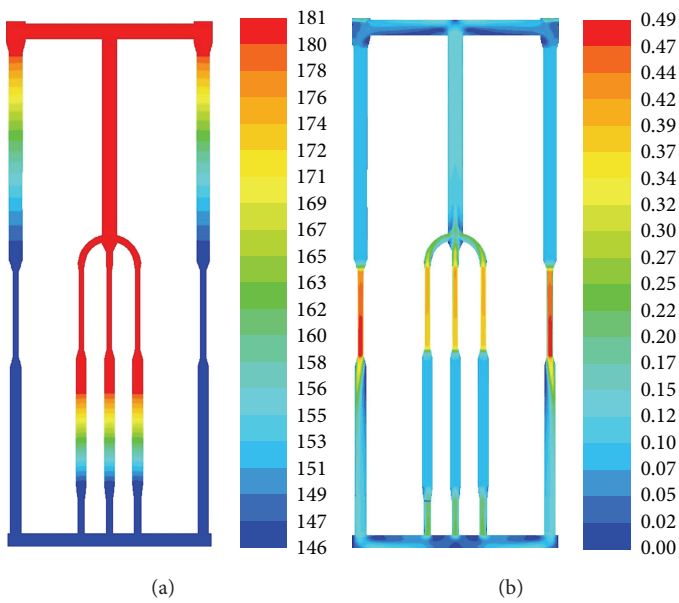

Figure 6: Flow fields in the test section: (a) temperature field; (b) velocity field.

(250°C) (Figure 10) and boiling will occur. This is dangerous to the reactor.

5.2. Effect of Configuration. The previous analysis showed that inclination caused the decrease of overall circulation ability and a disparity in branch circulation abilities. Optimizing the configuration of the loop may reduce these unwanted effects.

In order to reduce the disparity of different branch circulation ability, the outer force circuit (Figure 11) should be inhibited, while the inner force circuit should be enhanced. The ratio of the two driving forces is as follows:

$$\phi = \frac{Wg\sin\alpha}{H_0 g\cos\alpha} = \frac{2\tan\alpha}{\tan\beta}. \quad (2)$$

Equation (2) shows that an increase in β reduced the relative importance of the outer circuit driving force and then reduced the disparity in the branch circulation abilities (Figure 12). The difference between the mass flow rates of the two cold legs rapidly increased with the increase of inclined angle α for small values of β. This indicates that in order to control the influence of inclination, a long and thin reactor core is a better loop configuration for a reactor design.

5.3. Effect of Flow Resistance Distribution. The ratio between pressure drops of hot leg and cold leg also affected the magnitude of the disparity in the branch circulation (Figure 12). The disparity reduced with the decrease of $\Delta p_{HL}/\Delta p_{CL}$ (Figure 13). Therefore it is favorable to decrease the flow resistance coefficient, f, of hot leg (or increase, f, of cold leg) as well as increase the cross section area of flow channel, A, of hot leg (or decrease, A, of cold leg).

6. Conclusion

This paper experimentally and numerically investigated steady-state single-phase natural circulation under inclined conditions. Both experimental and numerical results showed that under inclined conditions the circulation ability was inhibited—the total mass flow rate decreased and ΔT increased. This was caused by the decrease of the average effective altitude. Furthermore, the driving force along the outer circuit of the loop had an opposite effect on the branch circulation and caused disparity in the branch mass flow rates. An increase in loop angle β (a reduction in width W) reduced the disparity in branch circulation and alleviated the decrease of the overall circulation ability. Furthermore, a decrease in the value of $\Delta p_{HL}/\Delta p_{CL}$ was also helpful for reducing the branch circulation disparity. The electrical heater elements will be overheated under large inclined condition because of the severe reduction of circulation flow rate.

Nomenclature

A: Cross section area [m^2]
c_p: Specific heat capacity [J/(kg · K)]
g: Gravity [m/s^2]
H: Altitude [m]
k: Natural circulation ability [W · K$^{-3/2}$]
m: Mass flow rate [kg/s]
N: Cold leg number
Nc: Loop component number
f: Resistance coefficient
T: Temperature [°C]
W: Loop width [m].

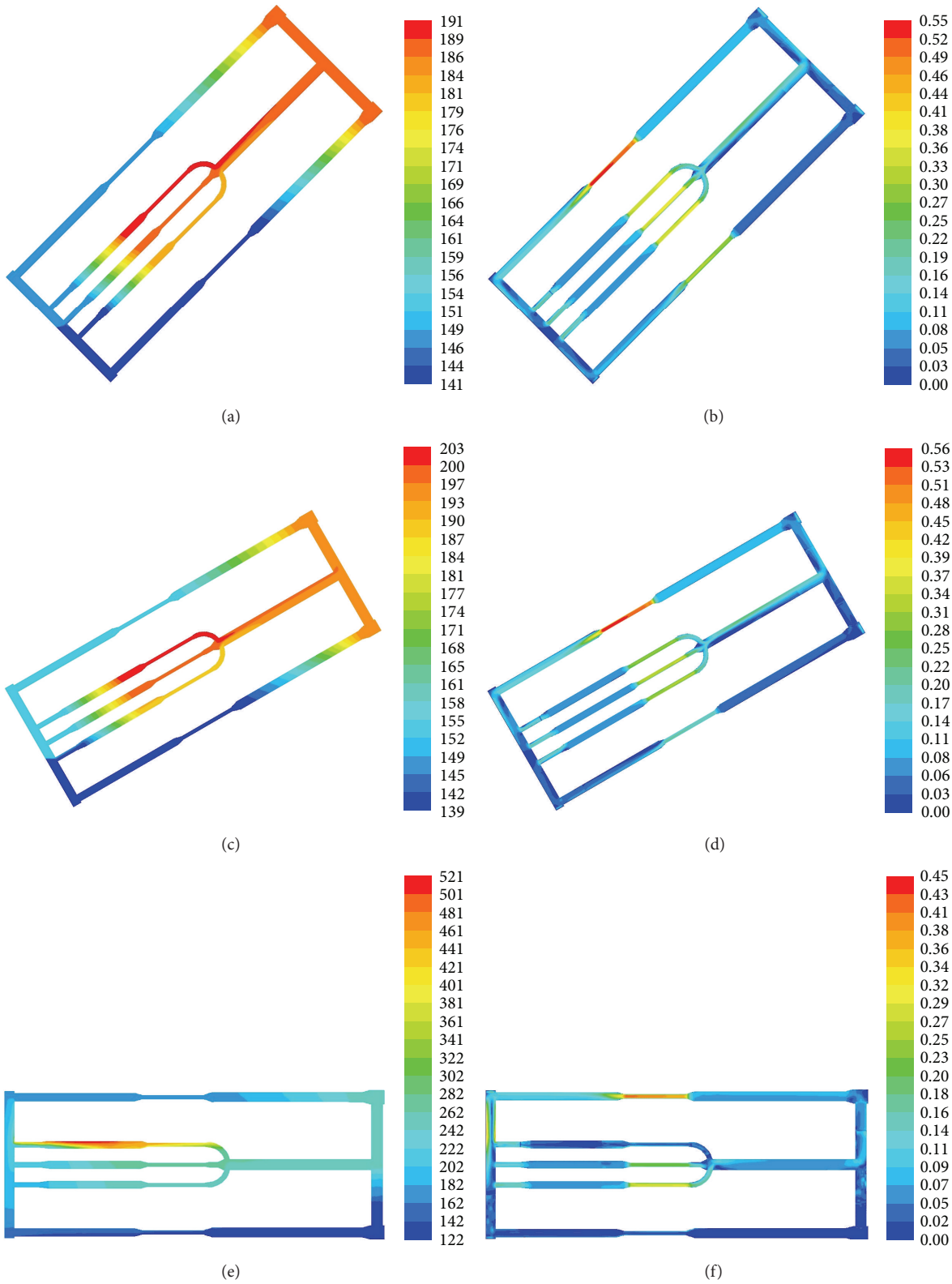

Figure 7: Flow fields in the test section: (a) 45°, temperature field; (b) 45°, velocity field; (c) 60°, temperature field; (d) 60°, velocity field; (e) 90°, temperature field; (f) 90°, velocity field.

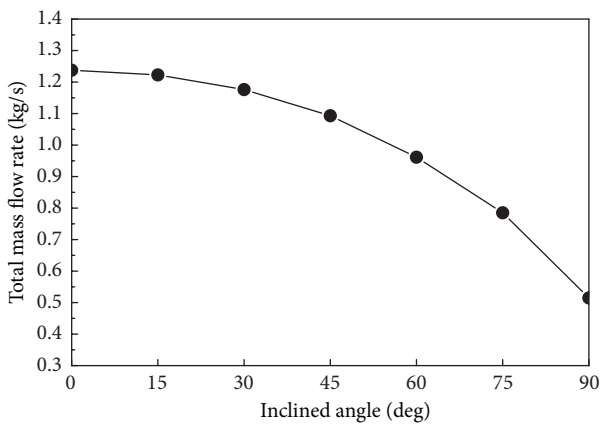

Figure 8: Total mass flow rate variation with inclined angle.

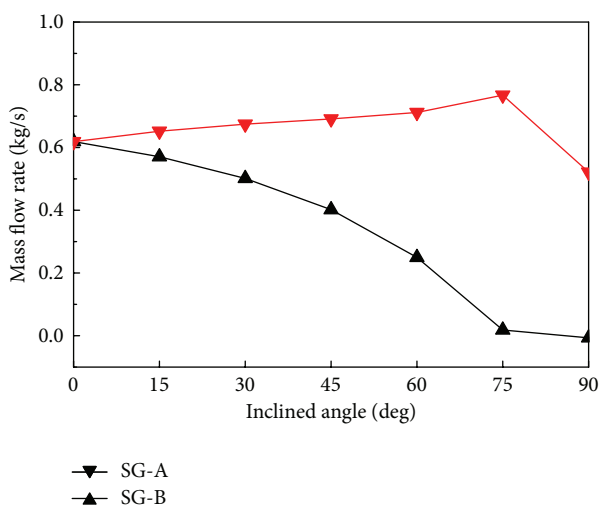

Figure 9: Branch mass flow rate variation with inclined angle.

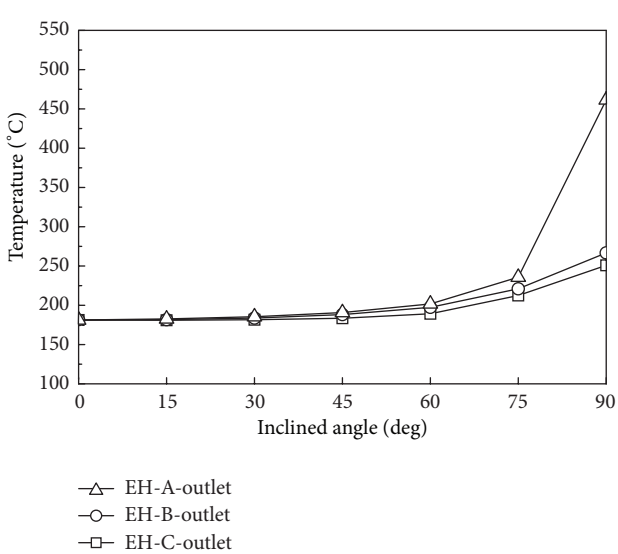

Figure 10: Outlet temperature of electrical heaters with inclined angle.

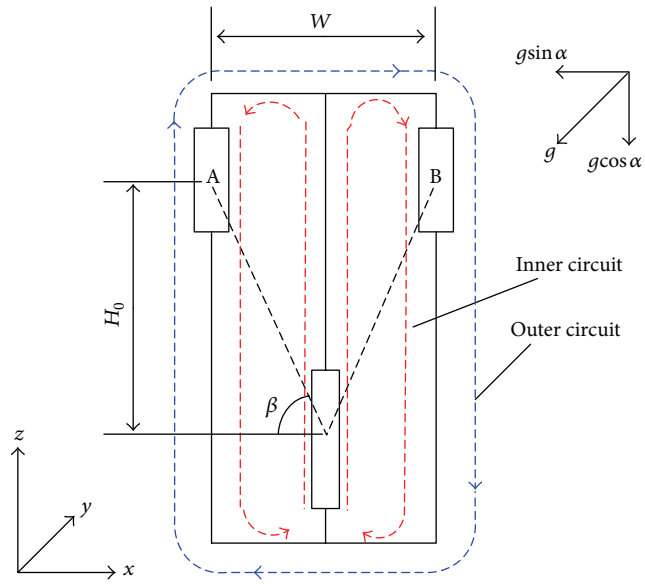

Figure 11: Mechanism of disparity of natural circulation ability.

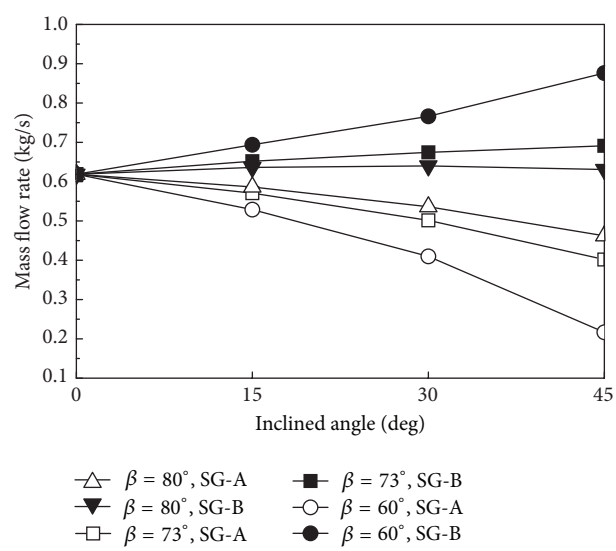

Figure 12: Effect of flow resistance distribution (experimental results).

Greek Letters

α: Inclined angle [degree]
β: Configuration angle [degree]
γ: Thermal expansion coefficient [K^{-1}]
δ: Mass flow rate ratio
ρ: Density [kg/m^3]
ϕ: Driving force ratio.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

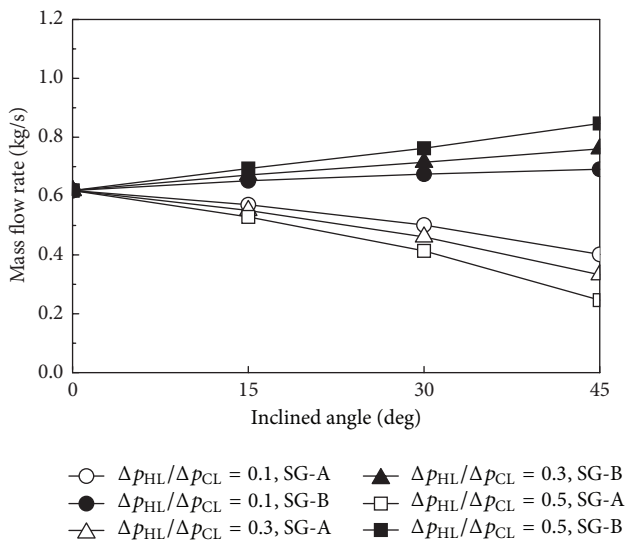

Figure 13: Effect of flow resistance distribution (experimental results).

Acknowledgments

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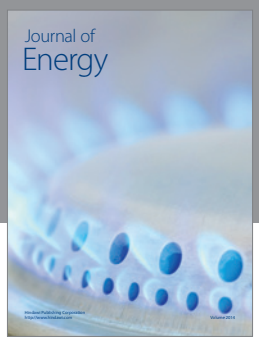

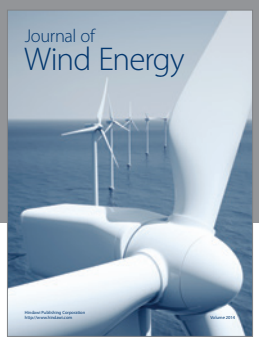

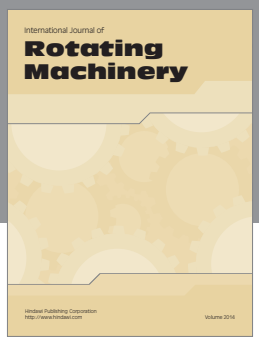

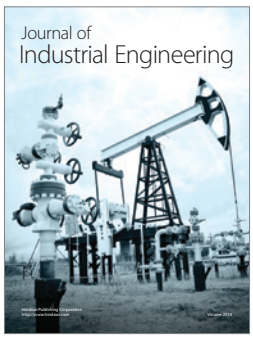

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