DESIGN AND PERFORMANCE OF SIMPLIFIED TEST LOOP FOR MOLTEN-SALT FLOW

H. Hashimoto, K. Amagai, H. Hiyama* and K. Yamamoto*

Institute of Fluid Science, Tohoku University, Katahira 2-1, Sendai, Japan
Ebara Research Co., Ltd., Honfujisawa 4-2-1, Fujisawa, Japan

ABSTRACT

Thermal-fluid dynamic data are essential for establishing the practical application of molten-salt. A simplified test loop was designed for obtaining highly accurate fundamental data on molten-salt flow. Flow rate calibration, pressure loss measuring and temperature control methods were also examined. Furthermore, assessments were made on flow rate fluctuation, temperature fluctuation and velocity distribution.

INTRODUCTION

Molten-salts have several important industrial applications. Molten-salt loops have been designed for developing molten-salt nuclear reactors (1,2,3). Molten-salts are also used as a substitute for other high temperature molten materials (molten slags, molten rock = lava, and other such high temperature flowing molten systems) in simulation tests. However, very few basic fluid dynamic research data on molten-salt flow are available.

The simplified test loop for molten-salt (hereinafter termed as 'test loop'), designed and developed by the authors, has made it possible to carry out experiments on fluid dynamic properties of molten-salt and to accumulate the much sought basic data on molten-salt flow. To confirm the operational performance of the test loop, studies were made on fluctuations in the flow rate and temperature of the molten-salt. The simple calibration systems of the flow meter and the pressure gauge were also studied. In the following design factors and operational performances of the test loop are presented. Data on the treatment of molten-salt, based on actual flow data, are also introduced.

FEATURES OF SIMPLIFIED TEST LOOP

671
The design of the test loop includes the following: [1] A test section for carrying out various thermal-fluid dynamic experiments, [2] A compact design, enabling manually controlled operation and easy maintenance, for using the test loop in a relatively small laboratory, [3] Ability to use the molten-salt (KNO₃-NaNO₃-NaNO₂; 7-44-49 mol%) as the test medium, [4] Ability to calibrate the flow rate measurement devices, and [5] Guarantee of a safe operation up to 400°C maximum.

Figure 1 and 2 show cross sections and a schematic diagram of the test loop, respectively. The total volume of molten-salt was 0.14m³. The 304 stainless steel was used for all part of the test loop as the corrosion rate of SUS304, exposed to molten NaNO₃-KNO₃ and under a temperature of 600°C(5), is approximately 2.5x10⁻⁶mm/year. In an attempt to avoid the thermal stress, a pump, tanks and pipes were mounted in such a way so that they could slide on their fixed support tables. The safety of the operation was confirmed by preliminary tests in which water was used as the medium for checking the cover gas pressure control and the valve behavior for the test loop operation under various pump speed ranges. Water was also used as the medium for investigating the pump and flow meter performances. Some details on the components of the test loop are discussed in the following.

Figure 3 shows a cross-sectional view of the test loop storage tank. The storage tank had an inner diameter of 600mm and a height of 600mm, and could hold 0.14m³ of molten-salt. A 6kW power electric resistance heater coils was applied around the tank for melting solid salt. Lagging materials, 150mm in thickness, were wrapped around the exterior tank as well. To enable visual observation of the molten-salt, the tank was equipped with some heat resistance glass windows (60mm diameter and 8mm thickness). Nitrogen was made to flow into the tank as the cover gas for preventing the molten-salt from absorbing impurities from the air. Molten-salt was transported from the storage tank, shown as D in Figure 1, into a pressure control tank, shown as © in the same figure, by the pressure force of the cover gas. Figure 4 shows a cross-sectional view of the pressure control tank. It was the same in size as the storage tank and had the function of preventing pressure surges due to temperature and velocity changes in the main loop. The fluctuation of the molten-salt flow rate was realized to be less than 1%. A stainless steel wire mesh was installed in the tank for degassing. Nitrogen gas was used here as a cover gas. The bulk pressure in the main loop molten-salt flow could be adjusted by simply adjusting the cover gas pres-
A magnetic coupling centrifugal pump, shown as 3 in Figure 1, was installed for molten-salt circulation in the main loop. Figure 5 shows a cross-sectional view of this pump. For cooling the motor and sealing off the molten-salt, the motor torque was indirectly transmitted to the impeller shaft by a magnetic force. The pump performance was set at 10^5 Pa and 1.67x10^{-3} m^3/s at 1460 rpm (see Figure 6). A good correlation between water and molten-salt, over a wide temperature range, was confirmed experimentally with regard to pump performance. The relation between the pump delivered pressure and the flow rate, at various temperature settings, was established as the physical properties of the molten-salt strongly depended on temperature. The total length of a main loop was 5 meters. The piping was covered with electric resistance heating coils and 70mm thick lagging materials. The main loop was also equipped with a 1.5m test section, shown as 4 in Figure 1. All pipes, with the exception of the test section, were set at an angle of approximately 2 degrees in an effort to prevent any residual molten-salt from remaining in the test loop after drainage. Asbestos sealing materials were used at the pipe flange. Results of a chemical compatibility test between asbestos packings and molten KNO_3-NaNO_3 confirmed its applicability at temperature ranges below 400°C (6). The test loop was equipped with several manually controlled ball-type valves for controlling the flow rate. Inconel type metal sealings were applied on the moving parts of the valves. The maximum heat resisting temperature of the valve was up to 500°C. The pipes and tanks were wrapped with electric resistance heating coils for controlling the temperature. Figure 7 shows the temperature control system. Thermal cement was applied around each heater to enable fast heat conductivity into the wall. Figure 8 shows a cross-sectional view of the insulation materials. Chromel-alumel thermocouples were installed on the pipe and tank walls. A mixing chamber (see Figure 9) was installed in the test section for checking the mean temperature of the flow. Figure 10 shows an example of temperature fluctuation and of input power supply by the heater. It was found that molten-salt temperature can be controlled within an error of 1%.

TEST SECTION

Two contraction nozzles, shown as 5 in Figure 1 were installed upstream the test section to enable a uniform flow. Figure 11 shows geometrical data of the nozzles. Nozzle-1 had an exit dia. 37.6mm while Nozzle-2 had that of 21.7mm. A high temperature pressure gauge was used to measure the
pressure, while a turbine flow meter was used to measure the mean flow rate. Accurate measurement on the velocity profile of high temperature molten-salt is considered to be very difficult. However, using the convenient analytical method, developed by one of the authors, in which the analytical results agree well with actual water velocity profiles, it was possible to estimate the velocity profile at the test section of the loop. Thus, highly accurate velocity distribution data at the inlet of the test section can be obtained through this convenient method with no need to measure the velocity. This analytical estimate, based on the potential flow, can be used for each specific nozzle geometric configuration. Cross-sectional velocity profiles at the nozzle inlet and outlet are assumed to be expressed in simple mathematical curves. If \( u \) represents the maximum velocity and \( U \) represents the cross sectional mean velocity, and the subscripts \( i \) and \( o \) indicate the nozzle inlet and outlet, respectively (see Figure 12), the relation between the outlet uniformity, defined by \( \Delta u_o/U_o = \Delta u/\bar{U}_o - 1 \), and the inlet uniformity, defined by \( \Delta u_i/U_i = \bar{u}_i/\bar{U}_i - 1 \), where \( \Delta u \) means the deviation from the mean velocity \( U \), can be expressed as in the following equation:

\[
\frac{\Delta u_o}{U_o} = \left( \frac{D_i}{D_o} \right)^4 \frac{\Delta u_i}{U_i} + b. \tag{1}
\]

The constant \( b \) is determined from Figure 13. The parameter \( x^* \) is \( x_p/L \), wherein \( x_p \) is the distance from the nozzle inlet to the inflection point of the nozzle and \( L \) is the length of the nozzle. For the 36.7mm exit dia. nozzle, \( D_i/D_o = 4 \) and \( x^* = 0.5 \). \( b \) is then determined as \( b = -0.001 \). Whereby a relatively great non-uniformity \( \Delta u_i/U_i = 1 \) leads to \( \Delta u_o/U_o = 0.003 \). This analysis finally reveals that the velocity profile at the nozzle outlet was approximately uniform, except in the area just adjacent to the pipe wall. It was confirmed through many examples of inlet velocity profiles that the use of the nozzles enables uniform and stable flow at the entrance of the test section.

The test section is used for carrying out various thermal-fluid experiments systematically and for measuring systems which require careful operational procedures. It can also be used in the research for developing high temperature pumps, for investigating high temperature gas-liquid multi-phase flow, for investigating the forced convection flow which accompanies local solidification for developing solidification valves, and so on.

**SYSTEMATIC MEASUREMENT OF MOLTEN-SALT FLOW**

*Calibration System by Volumetric Flow Meter; For engineering*
applications of molten-salt, accurate measurements of flow rates are essential. Such accurate measurements were made possible by a volumetric flow meter shown in Figure 14. The mean flow rate in the test loop was measured by this flow meter through the following procedure. The molten-salt was first introduced to the volumetric flow meter tank by controlling a valve. The ascending time of the molten-salt surface in the tank was then measured by two electric probes set at different levels. The volume corresponding to the distance between the edges of the two probes was then measured taking into consideration the thermal expansion of the tank. One problem that had to be solved was an error by the volumetric flow meter which is caused by the liquid surface disturbances. Introducing a baffle plate solved this problem and the ascending surface of the molten-salt in the tank was stable and completely smooth. The flow rate was adjusted by a valve and by controlling the pump rotational speed for the purpose of minimizing fluctuations in the flow due to shift in the liquid level in the pressure control tank. Such fluctuations were caused by the changes in pump suction head. A 12V, 60Hz alternate current was applied on the electric probes to prevent electrolysis. The maximum error in the flow rate measurement was estimated to be less than 1%. The molten-salt was transported back into the main loop utilizing the nitrogen gas pressure. The experimental results indicated that the calibration system by the volumetric flow meter should be installed in the test loop for the high accuracy measurements.

The turbine flow meter was calibrated by the volumetric flow meter using both molten-salt and water. The rotating speed of the magnetized impeller of the turbine flow meter was measured by a frequency counter. Data on molten-salts in various temperature were in agreement with water within 3%. As can be seen in Figure 15, measurement error in the large flow rate \( (6 \times 10^{-4} \rightarrow 3 \times 10^{-3} \text{ m}^3 \text{s}^{-1}) \) was \( \pm 2\% \). If the turbine flow meter is correctly calibrated using water, it can also be used for measuring the molten-salt flow, i.e. calibration using molten-salt becomes unnecessary.

**Differential Pressure Measuring System:** Two molten-salt manometers were designed and developed for measuring pressure losses between two points in the flow (see Figure 16). The differential pressure was determined by molten-salt levels in these manometers. Heat resisting glass was used for the tubes in the manometers and fluoridate rubber O-rings were used for sealing off the molten-salt and the gas. Nitrogen gas was added into the manometers as a pressure force. This measuring system is also useful when applied with an orifice, a venturi flow meter, or a solidification valve, and the like. Figure 17 shows an example of the
Various experiments using the simplified molten-salt test loop, which was designed and developed for carrying out thermal-fluid experiments, showed relatively satisfactory results due to simplicity of operation and accuracy in measurement. The test section was found to be adequate for enabling stable flow and temperature. The volumetric flow meter was also found to be effective for use with calibration devices for other molten-salt flow meters. All in all, the molten-salt test loop, including its measurement and control systems discussed in this paper, is useful for obtaining basic data in regard to high temperature molten systems.

REFERENCES

1. W.R. Huntley, Oak Ridge National Labs. Report, ORNL/TM-5540 (1976).
2. W.H. Hoffman and S.I. Cohen, Oak Ridge National Labs. Report, ORNL-2433 (1960).
3. Y. Kato, Molten-Salt, 24, 100 (1981), (in Japanese).
4. H. Hashimoto, K. Amagai, Y. Hosono, M. Takahashi and H. Hiyama, Modern Techniques and Measurements in Fluid Flows, S. Xjong and S. Xijiu, eds., International Academic Publishers, 418 (1989).
5. R.W. Bradshaw, Sandia National Labs. Report, SAND80-8856 (1980).
6. R.W. Bradshaw, Proceeding of 21st IECUC, 828 (1986).
7. T. Suzuki, T. Arai, H. Hashimoto and H. Nasuno, Mem. Inst. High Speed Mech., Tohoku Univ., 58 (1987), (in Japanese).
Figure 1. Molten-Salt Test Loop

1. Storage tank
2. Pressure control tank
3. Pump
4. Test section
5. Contraction nozzle
6. Volumetric flow meter
7. Turbine flow meter
Figure 2. Schematic Diagram of Test Loop

1. Storage tank
2. Pressure control tank
3. Pump
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6. Volumetric flow meter
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Figure 3. Storage Tank

Figure 4. Pressure Control Tank
Figure 5. Magnetic Coupling Pump

Figure 6. Pump Performance

Figure 7. Temperature Control System

Figure 8. Cross Section of Insulation
Figure 9. Mixing Chamber

Figure 10. Temperature Fluctuation

Figure 11. Data on Contraction Nozzle
Figure 12. Flow Model

Figure 13. Relation between $b$ and $\frac{Di}{Do}$

Figure 14. Volumetric Flow Meter
Figure 15. Measurement Error of Turbine Flow Meter

$\Delta Q/Q$: relative error of actual and measurement flow rate.

Figure 16. Molten-Salt Manometer

Figure 17. Data on Orifice Flow Meter

$A$ and $Re$ were defined by $Q(\pi d^2/4)^{-1}(2 \Delta p/p)^{-1/2}$ and $4 \rho Q/(\pi M D)$, respectively, where, $Q=flow\ rate$, $\Delta p=differential\ pressure$, $\rho=density$ and $\mu=viscosity$. 

682