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Development of Flow Regime Map inside a Vertical Pipe

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1. Introduction

One of the technical issues raised by the development of the HTGR (High Temperature Gas-cooled Reactor) is the mixed convection, which occur when the driving forces of both forced and natural convection are of comparable magnitudes. It is classified into laminar and turbulent flows depending on the exchange mechanism and also into buoyancy-aided and buoyancy-opposed flows depending on the direction of forced flow with respect to the buoyancy forces.

In laminar mixed convection, buoyancy-aided flow shows enhanced heat transfer compared to the pure forced convection and buoyancy-opposed flow shows impaired heat transfer due to the flow velocity affected by the buoyancy forces. However, in turbulent mixed convection, buoyancy-opposed flows shows enhanced heat transfer due to increased turbulence production and buoyancy-aided flow shows impaired heat transfer at low buoyancy forces and as the buoyancy increases, the heat transfer restores and at further increases of the buoyancy forces, the heat transfer is enhanced.

It is of primary interests to classify which convection regime is mainly dominant. The methods most used to classify between forced, mixed and natural convection have been to refer to the classical flow regime map suggested by Metais and Eckert [1]. The map is based upon only several experimental studies and the range of Reynolds number and Grashof number is far below the HTGR range.

The present work is to make the experimental plan to develop the flow regime map applicable to the HTGR ranges. In order to achieve large Grashof numbers, the analogy experiment method will be adopted and the heat transfer system will be simulated by the mass transfer system.

2. Classical Flow Regime Map

2.1 Literature Survey

Some of the literatures related to the classical flow regime map are reviewed. Figure 1 shows the classical flow regime map suggested by Metais and Eckert [1]. It consists of the data of several investigators. Martinelli and Boelter [2] suggested a theory by which heat transfer inside a vertical pipe for the mixed convection regime of both natural and forced convection under laminar flows could be calculated. Eckert et al. [3] performed the experiments to obtain information on the mixed convection in turbulent flows. They revealed that the flow regime can be subdivided into a forced convection regime, a natural convection regime and a mixed convection regime by Reynolds and Grashof numbers. Kemeny and Somers [4] investigated heat transfer coefficients and pressure drop for both water and oil. Hallman [5] performed the experiments on transition to turbulent and entrance length for both buoyancy-aided and buoyancy-opposed flows.

The mixed convection flows are influenced both by Reynolds and Grashof number and the governing parameter *Bo* should be the combination of both numbers. Lots of different combinations were used depending on the investigators; Gr/Re^n type parameter and Gr/Re^mPr^n ones.

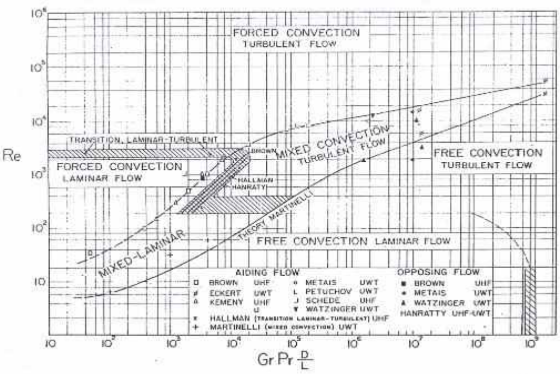

Fig. 1. Regimes of forced, mixed and natural convection inside a vertical pipe.

2.2 Problems

The issues are raised during the course of literature survey for the classical flow regime map in Figure 1: All of the investigators commonly used the diameter of the pipe *D* as the characteristic length scale for both Reynolds number and Grashof number instead of the height *H* of the pipe despite the fact that the buoyancy forces are proportional to the third power of the height of the hot wall. Only several studies were used for the development of the flow regime map and the data included in Figure 1 are even selected from the investigated literatures without explanations. In addition, the classical flow regime map was made only for Grashof number less than 10^9 and Reynolds number less than 10^5, which are lower ranges to apply to HTGR requiring the very large Reynolds and Grashof numbers.

3. Experimental method

3.1 Analogy Experiment Method

The achievement of large Grashof number with gas coolant requires very tall test facility as the Grashof number is strong function of facility height. In order to avoid tall and expensive test facility, this study will adopt the analogy experiment method. Using this, heat transfer system can be transformed into mass transfer system using the electroplating system. This system allows the large Grashof number to be achieved easily with short test facilities and accurate measurements of mass fluxes by electric means. Ko and Chung [6] performed a series of the turbulent mixed convection experiments inside a vertical pipe and showed that the analogy experiment method simulated the mixed convection heat transfer successfully and proved itself to be a useful tool for the draft estimation of the heat transfer rate in the highly buoyant system.

3.2 Apparatus and Procedures

Figure 2 shows a schematic of the test facility and system circuit. The test facility is basically acryl pipes of length 1.47m and inner diameter 0.035m, which is separated into three section; the upper, middle and lower section. Only the middle section is lined with a copper pipe of inner diameter 0.032m so that it may simulate the heated wall. The upper and lower sections are unheated entrance sections. In order to become fully developed flow conditions at the heated entrance, some of the flow straighteners are inserted in unheated section.

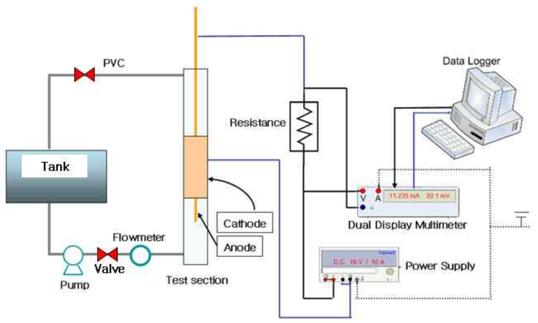

Figure 2. Schematic of the test facility and system circuit.

The test procedures are as follows. First step is the measurements of the Nusselt number for the pure forced convection at the very low Grashof number and the strong Reynolds number. If the measured Nusselt number for buoyancy-aided and buoyancy-opposed flows is same, it will be convinced that the Nusselt number of the pure forced convection is measured. The ratio of Nu_{Mixed}/Nu_F is used as the reference values. Second step is the measurements of the Nusselt number in the mixed convection regime by controlling the governing parameter *Bo* with decreasing the Reynolds number at the constant Grashof number. In this way, all of the tests for the wide ranges of Reynolds and Grashof numbers will be carried out for both buoyancy-aided and buoyancy-opposed flows.

4. Results

As a result of this study the experimental plan to develop the flow regime map inside a vertical pipe is represented in Table I. The ranges of Grashof number are from 2.7×10^6 to 2.2×10^{10} and those of Reynolds number are from 500 to 16000, which cover laminar to turbulent flows sufficiently than the classical flow regime map. The Prandtl number is varied from 2014 to 5771. As the Grashof number is proportional to the third power of the height, it is adjusted depending on the height of the pipe. Two kinds of the pipe with different diameter are used to vary the ratio length to diameter of 2 to 40.

Table I: Test matrix for mixed convection experiments.

Diameter (m)	Height (m)	Gr_H	Re_D	Pr
0.02, 0.032	0.04～0.8	2.7×10^6 ~ 2.2×10^{10}	500 ~ 16,000	2,014 ~ 5,771

5. Conclusion

The classical flow regime map is reviewed from the literature survey and it is realized that there are some issues on the reliability of the map. The present work is to make the experimental plan to develop the flow regime map applicable to the HTGR. The analogy experiment method using the electroplating system will be employed. As the deliverables of this study the experimental plan is established in Table I. From this, the flow regime map based on the height of the pipe *H* as the characteristic length will be developed at the wide ranges of Grashof number than those of the classical flow regime map.

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