Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 25-26, 2012

Problems of Mixed Convection Flow Regime Map in a Vertical Cylinder

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1. Introduction

One of the technical issues by the development of the VHTR is the mixed convection, which is the regime of heat transfer that occurs when the driving forces of both forced and natural convection are of comparable orders of magnitude. In vertical internal flows, the buoyancy force acts upward only, but forced flows can move either upward or downward. Thus, there are two types of mixed convection flows, depending on the direction of the forced flow. When the directions of the forced flow and buoyancy are the same, the flow is a buoyancy-aided flow; when they are opposite, the flow is a buoyancy-opposed flow.

In laminar flows, 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. In turbulent flows, however, 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]. During the course of fundamental literature studies on this topic, it is found that there are some problems on the flow regime map in a vertical cylinder.

This paper is to discuss problems identified through reviewing the papers composed in the classical flow regime map. We have tried to reproduce the flow regime map independently using the data obtained from the literatures and compared with the classical flow regime map and finally, the problems on this topic were discussed.

2. Process of Reproducing Flow Regime Map

In order to review and reproduce the classical flow regime map, we proceed up the procedures as below:

- ✓ Collected all the papers of investigators included in the flow regime map and reviewed them [2-7].
- ✓ Arranged the main contents such as boundary condition, working fluids, the range of *Gr* and *Re*, length scale, flow conditions, dimension of the cylinder, correlations.
- ✓ Extracted experimental data and the empirical correlations from the investigated information.
- ✓ Redraw the flow regime map independently using the investigated information.
- ✓ Compared the reproduced flow regime map with the classical flow regime map.
- ✓ Finally, reviewed the validation of the classical flow regime map and discussed the problems on the flow regime map.

2.1 Classical Flow Regime Map

Figure 1 shows the classical flow regime map suggested by Metais and Eckert in 1964 [1]. The horizontal axis is a combination of the *Gr* characterizing natural convection, multiplied by the *Pr* and the ratio of *D*/*L*. The vertical axis is the *Re* characterizing forced convection. The area surrounded by two curves is the mixed convection regime, where lower left corner is the laminar and upper right one is the turbulent mixed convection. In this area, when the *Re* increases or the *Gr* decreases, the flows become the forced convection. On the contrary to this, when the *Re* decreases or the *Gr* increases, the flows become the natural convection. This flow regime map consists of the results of 9 investigators and the data of various symbols is classified depending on buoyancy-aided and buoyancy-opposed flows as shown in the small box of Fig. 1.

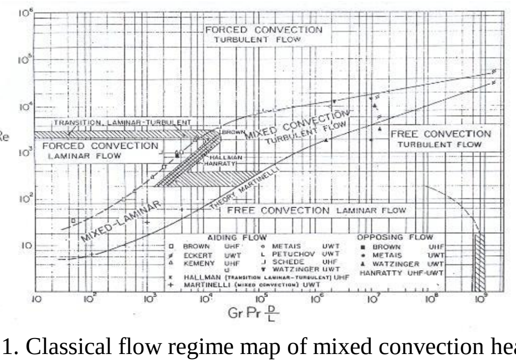

Fig. 1. Classical flow regime map of mixed convection heat transfer in a vertical cylinder [1].

2.2 Information in Literatures

Table I~III shows the data and mixed convection correlations to reproduce the flow regime map newly, which is obtained from the reviews of the 9 papers. Among them, the three studies of Brown, Petuchov, Metais and Eckert did not suggest sufficient information unlike other investigators but showed only the graphs.

Thus, it was unable to find the exact information such as *Gr* and *Re* and we used the approximate values by reading the graph's graduation.

Table I: Information in literatures.

	Hanratty et al.	Eckert et al.	Kemeny & Somers
Boundary condition	UHF, UWT	UWT	UHF
Flow	Transition, Laminar to turbulent	Turbulent	Laminar
Direction	Buoyancy-aided & opposed	Buoyancy-aided & Opposed	Buoyancy-aided
Pr	Water : 5.52	Air : 0.7	Water : 3~6, Oil : 80~170
Ranges	$3\times10^3 \le Gr_D \le 10^4$ $40 \le Re_D \le 350$	$36\times10^3 \le Re_D \le$ 37.7×10^4 $50\times10^3 \le Re_x \le$ 70×10^4 $10^9 \le Gr_x \le 10^{13}$	Water: $61 \le Re_D \le 6800$ Oil: $3.4 \le Re_D \le 630$ $10^2 \le Gr_D \le 10^5$
Length scale	Diameter (D)	Distance from heated wall (x)	Diameter (D)
L/D(m)	2.52/0.022	3.05/0.61	2.44/0.00635~0.0381

Table II: Information in literatures.

	Hallman	Martinelli & Boelter	Watzinger & Johnson
Boundary condition	UHF	UWT	UWT
Flow	Transition, Laminar to turbulent	Laminar	Laminar to turbulent
Direction	Buoyancy-aided & opposed	Buoyancy-aided	Buoyancy-aided & opposed
Pr	Water	-	Water: 2~5
Ranges	$10^4 \le Gr_D \le 4.5\times10^6$ $140 \le Re_D \le 4300$	-	$6\times10^6 \le Gr_D \le 10^8$ $1450 \le Re_D \le 15000$
Length scale	Diameter (D)	Diameter (D)	Diameter (D)
L/D(m)	0.92/0.008	-	1/0.05

Table III: Information in literatures.

Authors	Correlations
Martinelli & Boelter Eckert et al.	$Ra_D = 19.64(Gr_D)^{0.35}$ (Between forced and mixed) $Ra_D = 7.39(Gr_D)^{0.35}$ (Between natural and mixed)
Hallman	$Ra_D = 9470\left(\frac{\mathrm{Re}\,\mathrm{Pr}}{2x/D}\right)^{1.83}$ (Transition laminar-turbulent)

3. Results

Figure 2 shows the flow regime map independently reproduced from the information of literatures. It seems that both flow regime maps of Fig. 1 and Fig. 2 look similar each other. However, the issues are raised during the course of literature survey for the classical flow regime map in Fig. 1. It is apparent that there exist considerable differences between two figures (Fig. 1 and 2) and we are able to discover lots of the problems. Metais and Eckert [1] have used the data selectively to make the classical flow regime map despite the fact that there exist a lot of data in the previous studies. The line distinguishing the mixed convection regime is not the curves but the straight lines. Furthermore, we were not able to find any information about how to make the two curves. Transition area of left middle in Fig. 1 did not appear in the reproduced flow regime map of Fig. 2. All the papers consisting of the flow regime map had been done before 1964 and even any information on uncertainty analysis had not been suggested. All of the investigators commonly used the diameter *D* as the characteristic length for both *Re* and *Gr* 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.

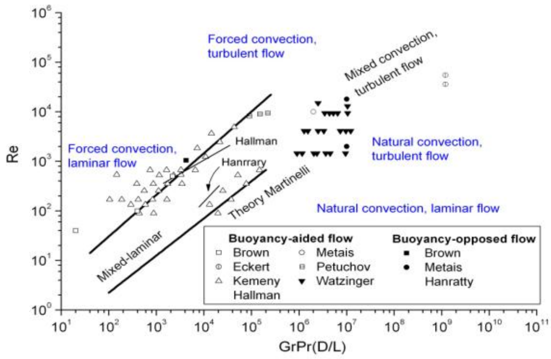

Fig. 2.Redrawn flow regime map.

4. Conclusions

This paper discussed the problems of the classical mixed convection flow regime map. As a result of investigating literatures, only limited data were used selectively for the development of the flow regime map without any explanations. Mixed convection regime taken as two curves and transition area were unable to be reproduced in Fig. 2. The information about uncertainty analysis and the evidentiary data were given insufficiently. In addition, the classical flow regime map was made only for *Gr* less than 10^9 and *Re* less than 10^5, which are lower ranges to apply to VHTR requiring the very large *Re* and *Gr* from the investigated literatures

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