Review of Mixed Convection Flow Regime Map of a Vertical pipe

Myeong-Seon Chae[a], Gyeong-Uk Kang[b] and Bum-Jin Chung[a*]
[a]*Department of Nuclear Engineering, Kyung Hee University,*
#1732 Deokyoung-daero, Giheung-gu, Yongin-si, Gyeonggi-do, 446-701, Korea
[b]*R&D Institute, Korea Radioactive Waste Agency, #111 989-Gil Daedeokdaero, Daejeon, Korea*
[*]*Corresponding author:bjchung@khu.ac.kr*

1. Introduction

Mixed convection is the regime of heat transfer that occurs when the driving forces of both forced and natural convection are of comparable orders of magnitude. This phenomenon is active area of research in a variety of engineering applications, such as nuclear-reactor cooling systems, solar-power generators, and heat exchanger [1]. In a vertical pipe, the natural convective force due to buoyancy acts upward only, but forced convective force can be either upward or downward. This determines buoyancy-aided and buoyancy-opposed flows depending on the direction of forced flow with respect to the buoyancy forces. Furthermore, depending on the exchange mechanism, the flow condition is classified into laminar and turbulent.

In laminar mixed convection, buoyancy-aided flow presents enhanced heat transfer compared to the pure forced convection and buoyancy-opposed flow shows impaired heat transfer as the flow velocity affected by the buoyancy forces. However, in turbulent mixed convection, buoyancy-aided flow shows an impairment of the heat transfer rate for small buoyancy, and a gradational enhancement for large buoyancy. The impairment of heat transfer is due to the laminarization. While, buoyancy-opposed flow indicates enhanced heat transfer due to increased turbulence production [2].

Several literatures are investigated to classify which convection regime is mainly dominant. The ways most used to classify between forced, mixed and natural convection have been to refer to the flow regime map by Metais and Eckert [3]. The map is based on several experimental studies and a detailed description for lines forming mixed convection and transition regime was not provided.

In this study, the existing flow regime map on mixed convection in a vertical pipe was reviewed through an analysis of literatures. Using the investigated data and heat transfer correlations, the flow regime map was reconstructed independently, and compared with the existing one.

2. Reviews

2.1 Flow regime map

Fig. 1 shows the classical flow regime map on heat transfer inside a vertical pipe suggested by Metais and Eckert. The parameter on the ordinate is the *Re*, presenting the degree of forced convective force and the parameter on the abscissa is the product *Gr* times *Pr* times *D/L*, the degree of natural convective force. The *Gr* is based on pipe diameter. The determination of the limits between the flow regimes requires some arbitrary definition since actually the transition of the mixed-flow region into the other two regime is asymptotic. The forced-flow regime will be defined as that part in which the influence of the *Gr* changes the heat transfer coefficient by not more than 10 percent. A corresponding definition will be applied to the limit of the free-convective regime [4].

Martinelli and Boelter [5] suggested the limits equation by which heat transfer inside a vertical pipe for the mixed convection regime of both natural convection and forced convection under laminar flows in equation (1). Watzinger and Johnson [6] also presented in equation (2).

Between forced and Mixed:

$$Re_D Pr\frac{D}{L} = 0.276\left(Gr_D Pr\frac{D}{L}\right)^{0.75} \quad (1a)$$

Between natural and Mixed:

$$Re_D Pr\frac{D}{L} = 0.0307\left(Gr_D Pr\frac{D}{L}\right)^{0.75} \quad (1b)$$

Between forced and Mixed: $Re_D = 19.64\left(Gr_D\right)^{0.35}$ (2a)

Between natural and Mixed: $Re_D = 7.39\left(Gr_D\right)^{0.35}$ (2b)

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.

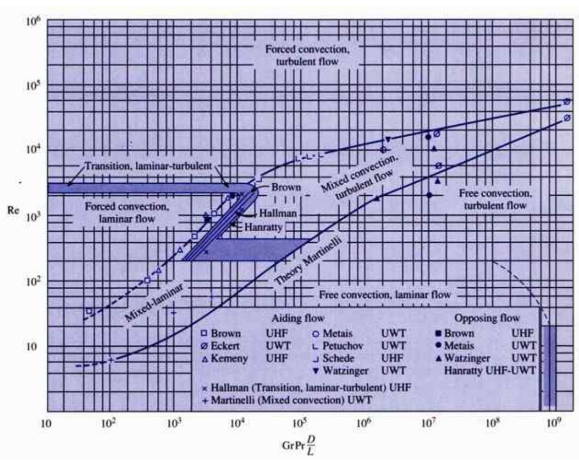

Fig. 1. Regimes of forced, mixed and natural convection inside a vertical pipe.

2.2 Limitations

The flow regime map should indicate the regimes for forced, mixed, and natural convection depending of the driving forces presented by the *Re* and *Gr*.

In spite of the fact that the buoyancy forces are proportional to the third power of the height of the heated wall, most of the investigators used the diameter of the pipe *D* as the characteristic length scale for both *Re* and *Gr*.

Some of the studies used to develop the flow pattern map were performed for constant temperature condition and others for constant heat flux condition. Those seem to be used without differentiation. Only several studies were used for the development of the flow regime map and the data included in Fig. 1 are even selected from the investigated literatures without explanations. Moreover, the range of classical flow regime map was too narrow to apply to the engineering such as HTGR requiring the very large *Re* and *Gr*.

3. Reconstruction of Flow regime map

Fig. 2 indicates the flow regime map reconstructed from the data of literatures. The area surrounded by two straight lines is the mixed convection regime. In this area, when the *Re* increases or the *Gr* decreases, the flows become the forced convection, On the other hand, when the *Re* decreases of the *Gr* increases, the flows become the natural convection.

It seems that both flow regime maps of Fig. 1 and Fig. 2 look similar each other. However, it is apparent that there exist considerable differences between two figures and we are able to discover lots of the problems. Metais and Eckert 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. There are no information of the how to make the two curves. If the two straight lines which limits between the forced flow and mixed flow were connected, it may become a curve. A corresponding it will be applied to the limits between the natural flows and mixed flows. Transition area of left middle in Fig. 1 did not reveal in the reconstructed flow regime map in Fig. 2.

Most of the papers consisting of the flow regime map had been done before 1964 and even any information on uncertainty analysis had not been suggested.

4. Conclusions

This study reviewed the limitations of the classical mixed convection flow regime map. Using the existing data and heat transfer correlations by Martinelli and Boelter and Watzinger and Johnson, the flow regime map was reconstructed independently. The results revealed that the existing map used the data selectively among the experimental and theoretical results, and a detailed description for lines forming mixed convection and transition regime were not given. And the information about uncertainty analysis and the evidentiary data were given insufficiently. The flow regime map and investigator commonly used the diameter as the characteristic length for both *Re* and *Gr* in place of the height of the heated wall, though the buoyancy forces are proportional to the third power of the height of heated wall.

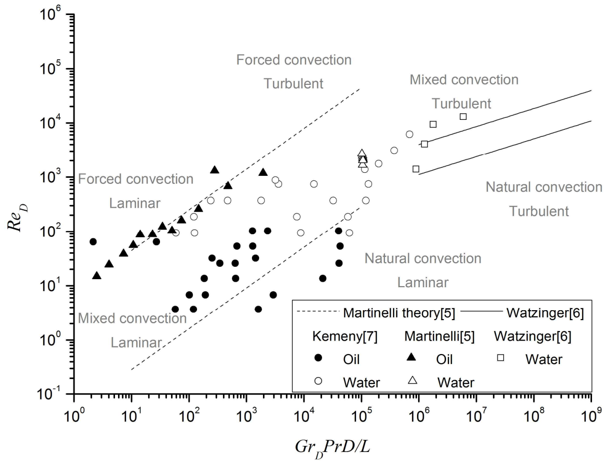

Fig. 2. Reconstruction of flow regime map.

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