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Impairment of Heat Transfer in the Passive Cooling System due to Mixed Convection

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1. Introduction

The adoption of passive cooling system has been increasing. The concept of passive safety is emphasized in design of nuclear power plant to accomplish the enhanced safety goal [1]. The passive cooling system focused on the natural convection cooling and heat transfer under accident conditions to remove the energy out of the containment. The Reactor Cavity Cooling System (RCCS) is the passive cooling system in Very High Temperature Reactor (VHTR) designed to remove the residual and decay heat.

In the passive cooling devices, the buoyant flows are induced. However the local Nusselt number of natural convective flow can be partly impaired due to the development of the mixed convective flows.

This paper discusses impairment of heat transfer in the passive cooling system in relation to the development of mixed convection. The present work describes the preliminary plan to explore the phenomena experimentally.

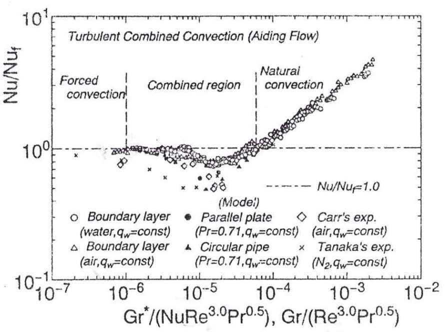
2. Background

2.1 Mixed Convection

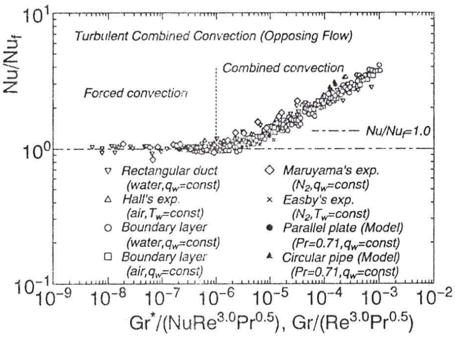
Mixed convection occurs when the driving forces of both forced and natural convection are of comparable orders of magnitude [2]. That is not intermediate phenomena with natural convection and forced convection but independent complicated phenomena.

In a vertical pipe, the direction of the buoyancy force is only upward but the forced convection can be either upward or downward flow. It determines buoyancy-aided and buoyancy-opposed flows depending on the direction of forced flow with regard to the buoyancy forces. Also, depending on the exchange mechanism, the flow condition is classified into laminar and turbulent flows.

In laminar mixed convection, the heat transfer of buoyancy-aided flow increases relative to the corresponding forced convection value. And the heat transfer of buoyancy-opposed flow decreases as the flow velocity affected by the buoyancy forces. While, in turbulent mixed convection, the trend is reversed. Buoyancy-aided flow shows an impairment of the heat transfer rate for small buoyancy due to the laminarization Fig. 1(a). And then, the heat transfer presents a gradational enhancement for large buoyancy. While, buoyancy-opposed flow indicates enhanced heat transfer due to increased turbulence production Fig. 1(b) [3, 4].



(a) Buoyancy-aided flow



(b) Buoyancy-opposed flow

Fig. 1. Turbulent heat transfer with mixed convection of a vertical flow system (Aiding flow) [3].

2.2 KAERI-RCCS Test Facility

The PMR200 (hydrogen producing VHTR) is being developed at KAERI(Korea Atomic Energy Research Institute). It adopts the RCCS (Reactor Cavity Cooling System) to remove the decay heat after the reactor shutdown during an accident [5]. RCCS is the passive safety system using the natural convection, which consists of cooling panels, they are placed in the reactor cavity. A 1/4-scale RCCS test facility, NACEF (Natural Cooling Experimental Facility) was constructed and experiments were performed to explore the safety the prototypic RCCS condition.

The natural convective air flow in riser tube corresponding to cooling panel of RCCS measured 1.9 m/s, when the temperature difference between inlet and outlet of riser tube is 100°C. Under the condition, the Nusselt number was calculated from the test results in quasi-steady state, and it compared with correlation of turbulent forced convection (Dittus-Boelter) and mixed convection (Symolon) as elevation of riser tube. They showed a fairly good agreement with a mixed convection correlation by Symolon. It means that the flow regime of long heated section in natural convection becomes the mixed convective flow regime. And the results of the heat transfer rates were impaired along the heated section axial position.

3. Analysis

When the natural convection occurs in the long enough heated section, the flow is developed by buoyancy forces. The flow regime becomes similar to the forced convection due to the duct flow condition. Thus, this force convective flow together with the local buoyancy effect can form complex mixed convective flow condition.

The local Nusselt number of the axial position pipe was partly impaired in certain local Grashof number and Reynolds number range correspond to the forced convection as shown in Fig. 2. Because the flow condition is influenced by locally buoyancy forces. And then, the local Nusselt number is recovered or enhanced by buoyancy forces depending on their magnitude. This can be associated with the recovery of turbulence concerned with buoyancy influences.

The Nusselt number distribution exhibits the non-monotonic behavior of mixed convection heat transfer which is naturally induced flow add to fan driven flow.

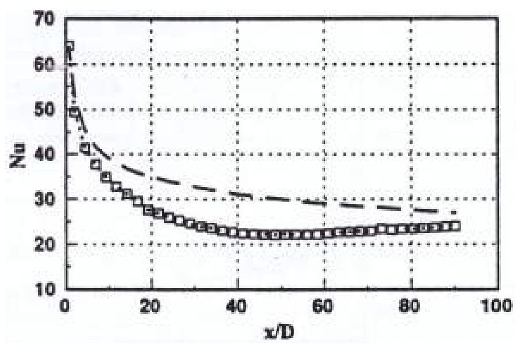


Fig. 2. Local Nusselt number distribution for natural convection (Gr_H=6.5×10^{12}, Pr=0.7) [4].

4. Preliminary Tests

The experiments are planned to investigate the riser tube phenomena of the NACEF.

Based on the analogy concept between heat and mass transfer processes [6], mass transfer experiments replace heat transfer ones so that large Rayleigh numbers could be achieved with reasonable test facility heights.

Table I shows the comparison of test range in NACEF and present test facility. The riser tube in NACEF has rectangular duct with the hydraulic diameter of 0.069 m. The present test facility was produced by circular duct as hydraulic diameter of 0.062 m, similar with NACEF. In order to same as buoyancy influences, it was set to be the equal Rayleigh number. It corresponds to the height of 0.15 m in present test facility. In addition, for the sake of satisfying the flow conditions, the Reynolds number was same with NACEF.

The elevation for impairment of the heat transfer in NACEF was about 1.2 m. Thus, it may be expressed elevation of 0.04 m – 0.05 m as the impairment of the heat transfer for present test facility

Table I : Comparison of test range in NACEF and present test facility

	NACEF	**Present test facility**
Test section type	Rectangular duct	Circular duct
D (m)	0.04m (L=0.24 m)	0.062
D_h (m)	0.069	0.062
H (m)	4.0	0.15
Velocity (m/s)	1.9	0.11
Re_{Dh}	6,300	
Ra_H	5.7×10^{11}	
Gr_H	8.0×10^{11}	2.7×10^{8}
Pr	0.7	2,094

Table II presents the test matrix. The diameter of cathodes was 0.017 m and 0.062 m. The diameter of 0.062 m correspond to hydraulic diameter of riser tube in NACEF. The Rayleigh number is adjusted depending on the height of the pipe, which covers a riser tube of NACEF. Reynolds numbers are to be varied from 100 to 15,000 for the laminar and turbulent mixed convection.

Table II : Test matrix

Pr	D_i (m)	H (m)	Ra_H	Re_D
2,094	0.017	0.15, 0.27	5.7×10^{11}, 3.3×10^{12}	100~15,000
	0.062			

Figure 3 shows a schematic diagram of the system circuit. It is a closed loop consisted of an acryl circular duct, a chemical pump and an electromagnetic flow meter and bypass system. The flow straighteners were employed at the unheated section, in order to achieve the hydraulic fully developed condition. Fluid flows from the reservoir through the pump and flow meter and then passes through the test section.

The piecewise electrodes were used as cathodes in order to measure the local average Nusselt number. The thin pipe was located the cathode as anode. Fig. 4 presents the piecewise electrodes of test section, they are electrically insulated by inserting very thin acyl sticks between them.

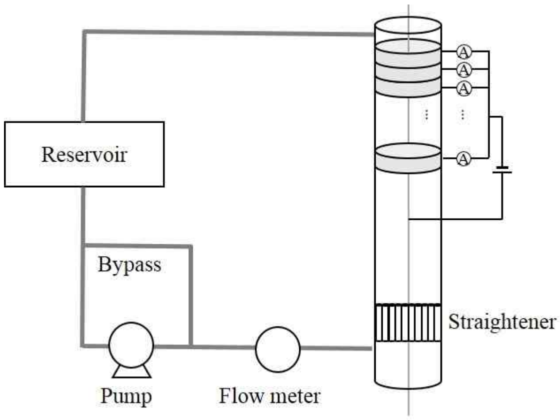


Fig. 3. Schematic diagram of the system circuit.

Fig. 4. Piecewise electrodes.

5. Conclusions

This paper is to discuss and make the plan to experiment the impairment of heat transfer in the passive cooling system due to mixed convection. In the sufficiently high passive cooling devices, the natural convection flow behavior can be mixed convection.

The local Nusselt number distribution exhibits the non-monotonic behavior as axial position, since the buoyancy-aided with mixed convection was appeared.

This is the part of the experimental work. And the deliverables of this study is design of the test facility and establish the test scope for similarity with NACEF.

The analogy between heat and mass transfer systems utilized, and an electroplating system was adopted as the mass transfer system. From this experiments, the phenomenological analysis will be developed in the heat transfer of mixed convection.

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