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Heat flux enhancement using particle-mixed coolant in HTGR

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1. Introduction

The most of the previous studies related to particle mixing for heat flux increase were focused on the water-based nano-fluid. In the case of water, nano-particles directly interact with the molecular layer of the wall and the cavity where bubbles ware produced. The particles help heat transfer and interrupt forming the bubble. By this process, particles contribute to enhance critical heat flux. However, in the case of gas, because gas is single phase fluid, the mechanism of heat flux enhancing by particles needs different from that of water. From the analytical model, there was the result that the radiation heat transfer and particles loading make heat flux gain. [1]

Here, as mixing ultra fine graphite particles into coolant in HTGR, this study will analyze the effect of heat flux enhancing from the heat radiation and the heat capacity increase. It is the purpose of this paper to investigate the feasibility of particle-mixed coolant in aspect of heat flux enhancement. The main concern is how much the maximum fuel (wall) temperature can be decreased.

2. Method

The fundamental equation was started from the energy equation. There are 4 assumptions to simplify the governing equation; no energy deposition from particle collision, uniformly dispersed particles, the velocity of particles which equals to that of fluid, sinusoidal core power distribution. In final, a heat balance in a channel flow yields the following two.

$$\rho_f C_f u_f \frac{\partial T_f(r,z)}{\partial z} = n_p h_p A_p \left(T_p(r,z) - T_f(r,z)\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r\left(k_f + \rho_f C_f \varepsilon\right)\frac{\partial T_f(r,z)}{\partial r}\right)$$

$$n_p V_p \rho_p C_p u_p \frac{\partial T_p(r,z)}{\partial z} = n_p h_p A_p \left(T_f(r,z) - T_p(r,z)\right) + n_p \sigma_a \sigma A_p \left(T_w^4(z) - T_p^4(r,z)\right)$$

These are subject to the initial condition

$$T_f(r,0) = T_p(r,0) = T_i \,,$$

and the next 4 boundary conditions.

$$\frac{\partial T_f}{\partial r}\Big|_{r=0} = 0 \,, \quad \frac{\partial T_p}{\partial r}\Big|_{r=0} = 0 \,, \quad T_p(R_c, z) = T_f(R_c, z)$$

$$\left(k_f + \rho_f C_f \varepsilon\right)\frac{\partial T_f}{\partial r}\Big|_{r=R_c} = q''_{conv}$$

The followings are the differences between the energy equation with particles and without particles.

▫ Fluid to particle heat deposition
▫ Wall to particles radiation heat transfer
▫ Particles to fluid convection heat transfer

The goal of solving the equations is to obtain the wall temperature distribution, T_w from T_f. To confirm the effect of mixing-particles, the particle concentration was varied. GT-MHR was selected to the reference gas cooled reactor and thus the environmental conditions were based on those of GT-MHR. [2]

3. Results

The particle-mixed coolant has the advantage that it can decrease the wall temperature at the same heat flux. More particles in coolant can make bigger wall temperature difference until the saturated amount of particles. The saturated particle concentration is about 4.5%, making over 300℃ gap as shown in Figure 1.

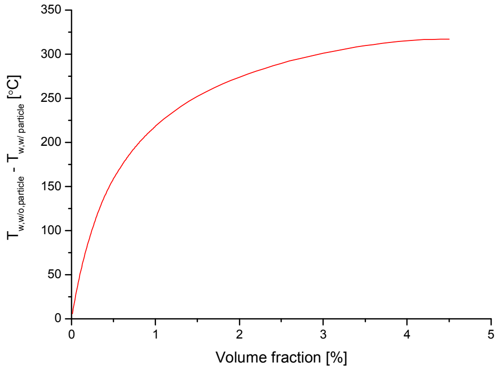

Figure 1. $\triangle T_w$ gain due to particles at the same heat flux

Mixing particle into coolant means that effective heat transfer area increase and total heat capacity is bigger due to the total huge heat capacity; the sum of that all particles have. Particles take the most energy from the heat flux; because the particle has thousand times bigger density and the sum of heat capacity all particles have becomes huge. There is another reason for decreasing the wall temperature. That is because of radiation heat transfer; in Figure 2, radiation heat flux gradually rises after middle since it depends on the wall temperature and the total heat flux. Though convection is the dominant heat transfer path, radiation heat transfer also contributes to the wall temperature decrease as much as about 20%.

As depicted above, particle-mixed coolant causes wall temperature decrease, and thus it gives the flux margin to increase when the condition, that the wall temperature at the condition of using particle-mixed coolant does not exceed the wall temperature at that of using no-particle coolant, is satisfied. The next question could be what percentage of particle volume should be needed and then how much heat flux can be increased at the specific particle volumetric fraction.

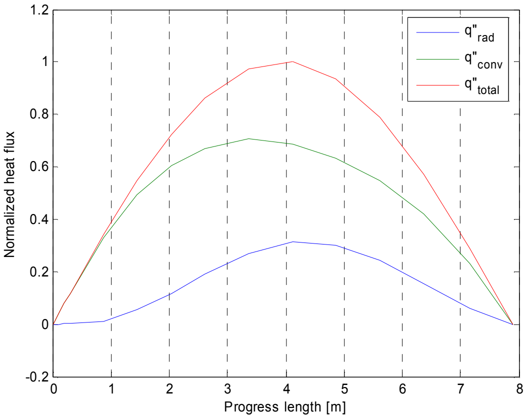

Figure 2. The effect of radiation heat transfer at 1% concentration, 10 ㎛ diameter particle, the same heat flux

As the number of particle rises, the energy which belong to particles rises and the total energy coolant have is increase shown in Figure 1. On the other hand, the energy of fluid decreases due to smaller heat capacity of fluid. This can be the problem when the heat exchanger is supposed to use only pure fluid. In GT-MHR the coolant passes through the turbine first after core exiting. Thus particle collides against the blades of the turbine and the turbine becomes to be worn away. In this case, particles should be ideally filtered out before entering the turbine. If so, as shown in Figure 3, only 5% heat flux increase at 0.55% particle volume fraction can be achieved. However, practically this process is impossible and useless. Better idea is to mix the reasonable small amount of particles into coolant, for example 1%, not to damage the turbine. In this case, totally 142% heat flux increase can be gained.

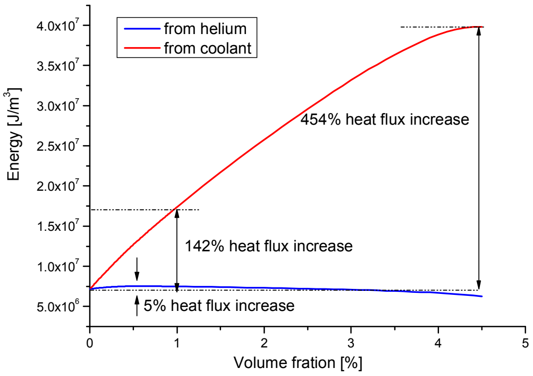

Figure 3. △q" due to adjusting the same wall temperature

The temperature distribution along with vertical axis is plotted in Figure 4. It is seen that 1% volume fraction is enough to decline the wall temperature.

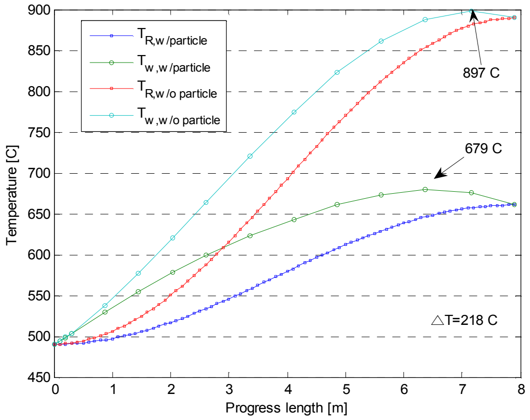

Figure 4. Temperature distribution at 1% concentration, 10 ㎛ diameter particle, the same heat flux

4. Discussion

The most important thing is that power up-rating may not be always desirable. If the power would be up-rated, several safety systems, such as an active decay heat removal system, should be required to satisfy safety criteria at the accident condition. Moreover, there are several problems to use the particle-mixed coolant. First, at accident condition, especially out of order for main pumps, particles could be sediment and this sediment would block the flow pathway. Second, particles can make the wall of path channels worn away and cause serious problem to important machine components by penetrating into the component inside. However, note that ignore other sophisticated problems, and the positive effect of mixing particles was treated here.

5. Conclusion

The heat flux can be improved by introducing particles to helium coolant in HTGR. The heat flux gain is increased up to approximately 2.4 times within the tolerable concentration, such as 1%. More particle concentration, more wall temperature gap. It leads heat flux to be enhanced.

In this study, the feasibility of heat flux increase from introducing graphite particle has been investigated. This work concludes that using mixed-particle coolant can improve heat transfer rate and the heat flux gain is occurred because of heat capacity increase and radiation heat transfer.

REFERENCES

[1] Zekeriya Altac and Nuri Yucel, An investigation for usage of graphite powder-helium suspension as reactor coolant in a HTGR, Nuclear Engineering and Design, Vol.131, 1991.

[2] Francois G. Cocheme, Assessment of Passive Decay Heat Removal in the General Atomic Modular Helium Reactor, Master's thesis, MIT, 2004.