§3. Basic Evaluation of Instability of Flow Rate and Temperature in Parallel Cooling Flows

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In order to shorten the cool-down time of large scale cryogenic devices, parallel cooling flows are necessary because of the limit of the pressure drop. However, there is an instability of temperature in cooling down process in parallel flows. Since the flow rate becomes larger at lower temperature under a constant pressure drop, the temperature difference is accelerated in parallel flows. Furthermore, the flow rate increases drastically after phase transition from gas to liquid. I have estimated the temperature change in simple models of parallel flows to know its basic features.

At first, I considered an object such as a thermal shield which is cooled by gaseous He. The pressure drop of a turbulent flow ΔP is expressed by Blausius's equation as

$$\Delta P = 0.3164\left(\frac{\rho \cdot d \cdot v}{\mu}\right)^{-0.25} \cdot \frac{\ell}{d} \cdot \frac{\rho \cdot v^2}{2} = 0.2414 \cdot \frac{\mu^{0.25} \cdot q^{1.75} \cdot \ell}{\rho \cdot d^{4.75}} \quad (1)$$

where ρ, v and μ are a density, a velocity and a viscosity of He. d and ℓ are diameter and length of the cooling pipe. q is a mass flow. The cooling power Q is given as

$$Q = q\int_{T_{in}}^{T_{out}} c \cdot dT \approx c \cdot q \cdot (T_{out} - T_{in}) \quad (2)$$

where c is specific heat of He. T_{in} and T_{out} are inlet and outlet temperatures. A calculated result for a simple model is shown in Fig. 1. It shows that the cooling power of gaseous He under the constant pressure drop is monotone increasing versus an outlet temperature. This means the reached temperature is uniquely determined by the amount of heat load. Even if some flows delayed in cooling, they catch up finally as far as the heat input and the length of pipes are equalized. Dashed lines are typical heat input, and it shows that the reached temperature is changed widely by the heat input.

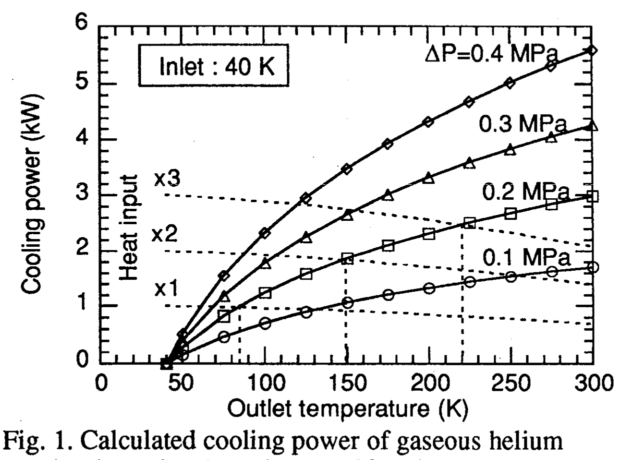

Fig. 1. Calculated cooling power of gaseous helium flowing in a pipe (ϕ11.4 mm, 100 m long).

Next, I calculated the temperature change of models of two parallel flows. Figure 2 shows typical results in the case that objects of different weight by 10% are cooled by liquid N_2 under a constant total flow rate. One is a case without heat exchange between two flows, and another is a case with heat exchange equal to the heat input. In these calculations, I considered an ideal object with very high thermal conductivity, and the pressure drop was estimated at the temperature equal to the object. It shows that the temperature difference between two flows becomes larger and larger as procedure of cooling. After either flow reaches the boiling point of N_2, the flow rates change drastically and the temperature of the delayed flow begins rising. In the model without heat exchange, the temperature of *Flow 2* reaches almost 250 K finally. Heat exchange between the parallel flows suppresses this instability. In the model with heat exchange equal to the heat input, the temperature difference just before the phase transition is reduced to 16 K from 26 K. Besides, the final temperature of *Flow 2* is lowered to 165 K. The final temperature difference in the two flows becomes half by the heat exchange.

The parallel flows have an instability of temperature, especially in the case accompanying a phase transition. In order to reduce the instability, heat exchange between the parallel flows is effective. Though the instability is weak in the case of gaseous He, the heat input and length of cooling paths should be carefully equalized to attain a uniform cool-down.

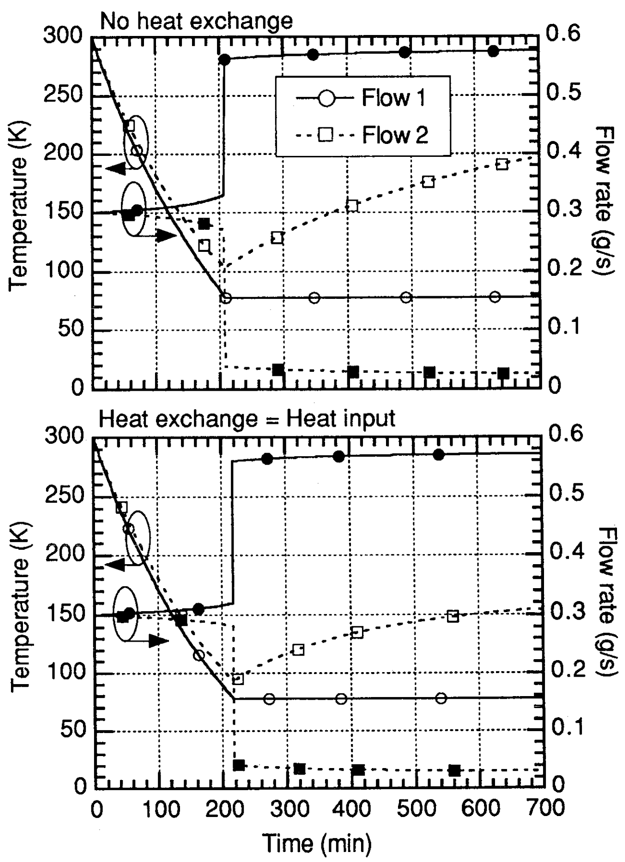

Fig. 2. Calculated temperature changes of two parallel flows with different weight by 10%. The coolant is liquid N_2, and the total flow rate is 0.6 g/s constant. Heat input is 0.155 W/K per each, the weights are 12.39 kg (Flow 1) and 13.63 kg (Flow 2), and the flow length is 21.7 m.