

**SUPPRESSION AND CONTROL OF THERMAL FATIGUE
BY AN ACTIVE FLOW CONTROL MAGNET (AFCOM)
; CONSTRUCTION OF MHD SIMULANT FLOW LOOP USING LIQUID-GALLIUM**

K. Yuki¹ and H. Yamano²

¹ Tokyo University of Science, Yamaguchi, Sanyo-Onoda, Yamaguchi, Japan

² Japan Atomic Energy Agency, O-arai, Ibaragi, Japan

Abstract

This study proposes a portable type of active flow control magnet (AFCOM) which would comprehensively solve thermal hydraulic issues such as thermal fatigue, flow-induced vibration, cavitation, etc. concerned in a sodium-cooled fast reactor. This AFCOM technology utilizes electromagnetic force that negatively affects for conducting fluid in general. To begin with, the applicability of the AFCOM technology to the sodium thermal hydraulic issues is evaluated from the thermal and MHD points of view and then, the details of a newly constructed flow test loop, which uses liquid gallium as the simulant of sodium, are reported, including the safety and corrosive issues of gallium.

1. Introduction

The most significant issue for energy security and environmental problems is to secure a permanent and low-load energy source. Based on this concept, in Japan, the strategy of practical application of sodium-cooled fast reactors, JSFR (The Japan Sodium-cooled Fast Reactor: see Fig. 1), has been rapidly promoted. The current design that aims toward the start-up of a demonstration reactor in 2025 simplifies the piping system in order to reduce amount of material. However, there still exist a lot of engineering issues that should be resolved. Such issues related to thermal hydraulics especially include flow-induced vibration, thermal striping, gas entrainment on a free surface, and corrosion. Problems caused by large-scale vortices rather than turbulent fluctuation are of a concern. These phenomena, except the gas entrainment on a free surface, could not only exert a devastating impact on the thin-walled pipe design that is one of the advantages of the sodium fast reactor, but also could further complicate the conservative domestic maintenance system, leading

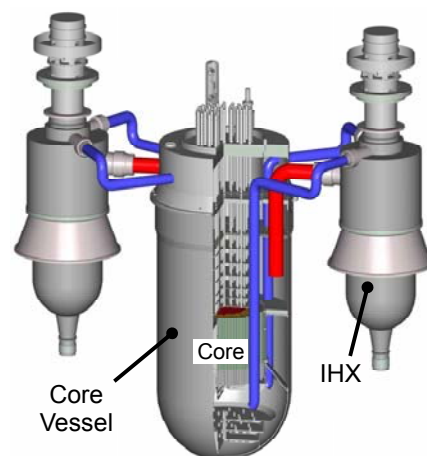


Fig.1 Bird's-eye view of JSFR

to the result of having long examination periods. Namely, these phenomena are the important R&D issues that directly connect to the soundness and profitability of fast reactors and the resolution of these issues is urgent. Domestic as well as international thermal hydraulic studies of sodium fast reactors have developed understanding of detailed flow structures such as thermal fatigue, flow-induced vibration, and cavitation. However, on the other hand, active secure measures and mitigation techniques for such flow structures have not been established.

For many years, by the way, the author has been conducted not only studies on thermal hydraulic issues represented by thermal fatigue in fast reactors and flow-induced vibration [1-5], but also studies on liquid metal utilized for liquid blankets of nuclear fusion reactors and high temperature molten salt [e.g. 6-12]. In particular, the author has promoted the fundamental study of the increase of pressure loss due to electromagnetic force generated by applying a magnetic field to the conducting fluid and the reduction of turbulent heat transfer. It is common knowledge that an applied magnetic field reduces turbulent fluctuations within the conducting fluid which could result in laminarization where the magnetic field has a strong influence. Where the influence of a magnetic field significantly increases, large-scale and low-frequency vortices such as Karman vortices, which have a significant impact on the above-mentioned thermal hydraulic issues, become stationary and then finally disappear. This phenomenon has been also clarified by numerical simulation [9, 10]. This fact is a positive finding from the standpoint of mitigating flow-induced vibration and thermal fatigue, which is caused by Karman-like vortices generated in a low curvature bend or fluid mixing area. In other words, the electromagnetic force, which usually acts in a negative way on the flow of conducting fluid, comprehensively acts in a positive way from the standpoint of the maintenance technology to act against thermal hydraulic issues of fast reactors. The electromagnetic force has the possibility to be put into practical application as active flow control technology. In addition, the effects below can be expected where a permanent magnet can be used as the external magnetic field.

- (1) Indirect applied magnetic field has less impact on the current design of fast reactors
- (2) Pressure loss does not matter because of the locally applied magnetic field
- (3) The road map for technical development of commercial reactors can be simplified
- (4) Simplified maintenance systems can enhance availability and economic efficiency
- (5) Magnetic fields can be applied from the outside of a thermal insulator, producing no operational cost

This technology has sufficient possibility to be the advanced fundamental technology which supports fast reactors. Ideally, it is desired to develop the active flow-control magnet (AFCOM), which is a demountable magnet installed on a target piping portion.

To develop the above-mentioned concepts as a maintenance technology to act against thermal hydraulic issues for sodium-fast reactors, it is absolutely essential to demonstrate the principles of the above concepts by performing experiments. Moreover, it is also important to develop the concepts as a controlled technology by generalizing those phenomena so as to obtain the direction for practical application. The ultimate goal of this research is to demonstrate the principles of the maintenance

Table 1 Specifications of gallium

Melting point	29.78 deg. C (Boiling point 2204 deg.C)			
Specific gravity	6.09 (Liquid), 5.9 (Solid) ※ expansion at solidification			
Heat of melting	5.59 kJ/mol			
Vapor pressure	9.31 x 10 ⁻²¹ Pa (302.9 K)			
Specific heat	370 J/kg/K			
Electric conductivity	3.85 x 10 ⁶ (1/(m·Ω)) @29.8 deg.C 3.70 x 10 ⁶ (1/(m·Ω)) @100 deg.C			
Thermal conductivity	25.5 W/m/K @29.8 deg.C 30 W/m/K @100 deg.C			
Corrosiveness	Glass	◎	Copper	△
	Polyvinyl chloride	◎	Aluminum	×
	Ceramics Acrylic, Teflon	◎ Bad Wettability	SUS316L	○
			Rubber	?
Hazardous property (MSDS sheet)	•Non-toxicity (No reports for industrial exposure) •Ingested Ga isn't absorbed inside body (Insoluble compound) •Stable under atmospheric condition			

technology, AFCOM, that controls thermal fatigue and flow-induced vibration by the use of permanent magnets, and to obtain the perspective for specific engineering applications of this technology. As for the first step, this paper reports on an experimental flow-test facility that utilized liquid gallium as the simulant of sodium was produced based on the magneto-hydrodynamic (MHD) view.

2. MHD Simulant for Liquid Sodium

2.1 Handling and Safety of Gallium

In this research, gallium is selected as the simulant of sodium from a number of molten metals. Sections 2.1 and 2.2 outline the reasons as to why gallium was selected. Table 1 shows the major characteristics of gallium. Gallium is a low melting metal with a melting point of 29.8 degrees Celsius and a specific gravity of 6.09 when it is a liquid. Gallium has almost the same thermal conductivity as stainless steel. This liquid metal has low vapor pressure and is very easy to handle. As for corrosiveness which is of concern, gallium works well together with glass, polyvinyl chloride, Teflon, acrylic, and ceramics. However, the wettability of gallium does not work well together with Teflon or ceramics, thus it is probably impossible to utilize as material for the heat transfer test section. With respect to the use of metals, corrosiveness under high temperature arouses concern, whereas it appears that corrosiveness for copper, hastelloy, and stainless steal at normal temperature does not matter. However, care needs to be taken in this regard since no data about prolonged use of such metals has been obtained. It should be noted that it is impossible to use aluminum or aluminum alloy as the experimental apparatus material because of the strong corrosive effect gallium has on aluminum. Next, when the material safety data sheet (MSDS) is referred to for safety information, it reports that gallium is basically a

nontoxic material and there have been no hazardous property reports due to industrial exposure. Orally-ingested gallium becomes an insoluble compound and is not absorbed into the body. Gallium is also a stable material even when exposed to the atmosphere. In summary it can be said that gallium, having the above-mentioned characteristics, is a suitable material for experiments performed in a university laboratory. Therefore, sound hydraulic experiments can be expected depending on the selection of material.

Table 2 Comparison of major physical properties

<u>Liquid gallium @ 32deg.C</u>	<u>Liquid sodium @ 300 deg.C</u>
Density: $\rho = 6.095 \text{ kg/m}^3$	Density: $\rho = 0.880 \text{ kg/m}^3$
Coef. of vol. expansion: $\beta = 1.26 \times 10^{-4} \text{ 1/K}$	Coef. of vol. expansion: $\beta = 2.7 \times 10^{-4} \text{ 1/K}$
Thermal diffusivity: $a = 1.18 \times 10^{-5} \text{ m}^2/\text{s}$	Thermal diffusivity: $a = 6.53 \times 10^{-5} \text{ m}^2/\text{s}$
Kinematic viscosity: $\nu = 3.22 \times 10^{-7} \text{ m}^2/\text{s}$	Kinematic viscosity: $\nu = 3.92 \times 10^{-7} \text{ m}^2/\text{s}$
Pr number : 0.025	Pr number : 0.006
Electric conductivity: $\sigma = 6.78 \times 10^6 [1/\Omega\text{m}]$	Electric conductivity: $\sigma = 5.69 \times 10^6 [1/\Omega\text{m}]$

2.2 Applicability of liquid gallium as the Na simulant

This section discusses the applicability of liquid gallium as the simulant of sodium. Table 2 shows the comparison of major physical properties regarding the thermal and electrical characteristics of liquid gallium and liquid sodium. First, the applicability of Ga as a thermal hydraulic simulant is discussed here. The kinematic viscosity of each material is almost at the same level; the same Reynolds number can almost be achieved if these liquids are circulated at the same flow velocity using a pump. On the other hand, gallium has the Prandtl number about four times that of sodium, which sufficiently falls into the range of discussion. Next, the applicability as the MHD simulant is focused on. The electric conductivity of each material is almost at the same level. However, since gallium has a high density, sodium has a higher Hartmann number that is an important parameter related to the MHD fluid as shown in Figure 1. This fact actually implies that success in MHD control of gallium also leads to successful result also in sodium case. For instance, where the length of an area where the magnetic field is applied is 0.03 m and a permanent magnet with the magnetic flux density of 0.5 T is used, the Hartmann number of gallium is also quite high, which is in the Order of 10^2 , thus conditions with a high Hartmann number can be achieved. Figure 1 on the right shows the interaction parameters that are very important when considering interactions between the flow and the magnetic field. According to the prediction of Karman vortices control performed by Mutshke et al., where the Reynolds number is below 10^3 , the critical N that shows the transition to the

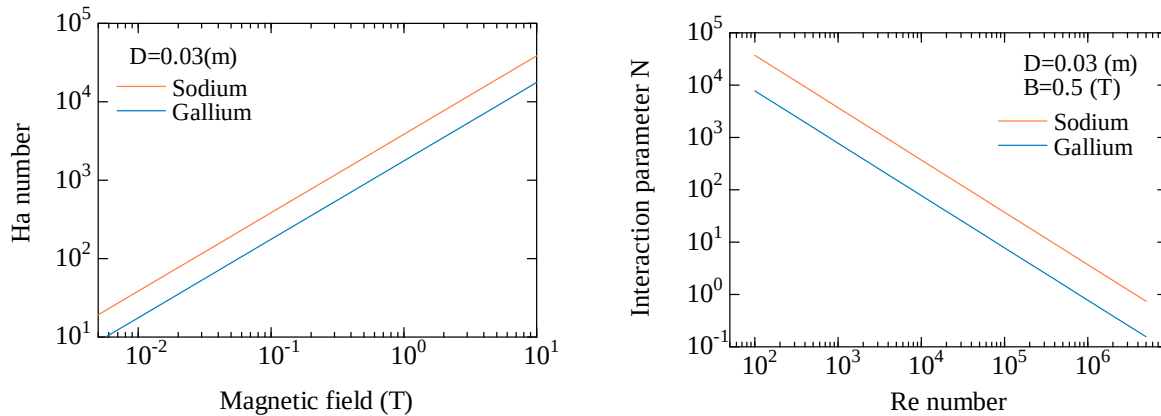


Fig. 1 Comparison of Hartmann number and interaction parameter

stationary vortices from Karman vortices seems to increase as the Reynolds number increases.

However, its value is below 1. It is probable that the critical N also increases under the conditions with much higher Reynolds number; however, interaction parameters are sufficiently high if the Reynolds number is as high as up to Order 10^4 . This can make it possible to control vortices. In particular, as far as the author knows, there exists no data regarding vortex control under high Reynolds numbers.

3. Construction of the Liquid Gallium Flow Test Loop

3.1 Details of experimental apparatus

Figure 2 shows the schematic of the liquid gallium flow test loop. The experimental apparatus consists of the circulation pump, the test section, the upper tank, the flow rate measuring section, the heat exchanger, and the drain tank. Most parts of pipe material are composed by transparent polyvinyl-chloride pipes and polyvinyl-chloride joints in order to prevent corrosion and to monitor the flow status of the liquid metals by visual inspection. The inner diameter of the main pipe is 21.0 mm. The loop is a vertical one, about 1.5 m long and 0.5 m high, and the internal volume of gallium is approximately 4.0 L. The horizontal pipe of the loop slightly slopes so that all gallium can be spontaneously collected into the drain tank in case of emergency such as an earthquake. In addition, the drain tank is installed at a location lower than the loop. The circulation pump used here is a canned pump which has been used for circulating mercury, and all parts including the casing and the impeller are created by using stainless steel (SUS316L). The total pump head is 10 m with 150 L/min maximum flow rate. The casing of the canned pump has a double structure. This makes it possible to adjust the fluid temperature of the Ga by circulating water into the external container. The temperature of this water is regulated by using

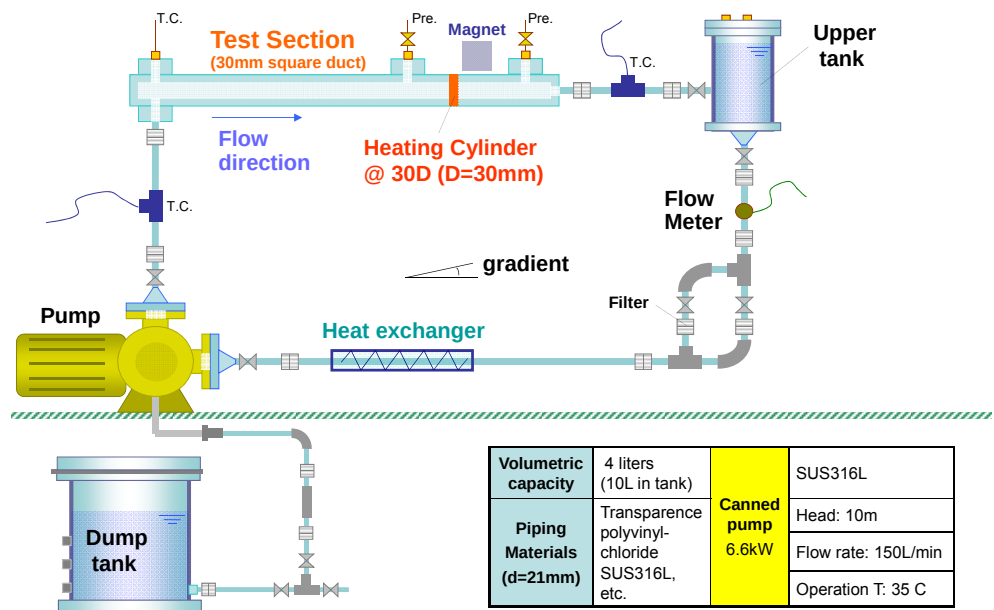


Fig. 2 Experimental Ga-flow test loop

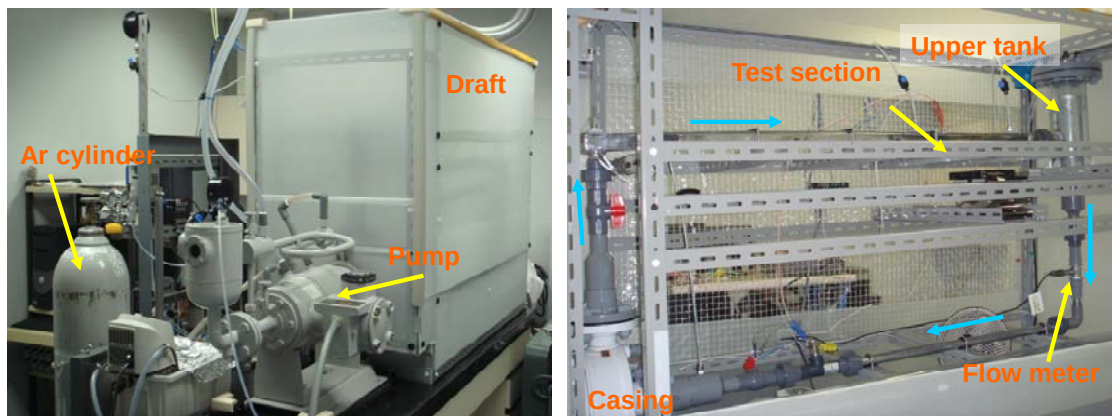


Fig. 3 Overview of liquid Ga flow test loop

a chiller. The upper tank mainly serves to confirm the filling status of liquid and deaeration. The flow rate is measured by using a turbine flowmeter. Figure 3 shows the overview of the experimental apparatus. This apparatus, except for the pump, is surrounded with a draft created by using thermal insulating panels. Installed inside the draft, there is a ceramic heater for increasing the room temperature and a mixing fan that makes the room temperature uniform. The temperature is maintained from 35 degrees to 40 degrees C. by the ceramic heater and mixing fan. The length of the test section measures 1500 mm. The magnetically controlled

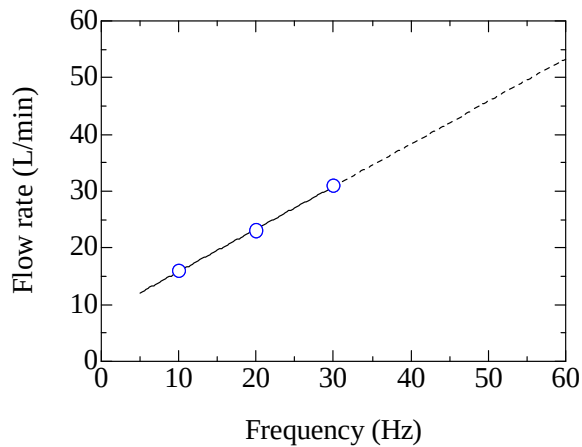


Fig. 4 Flow rate characteristics

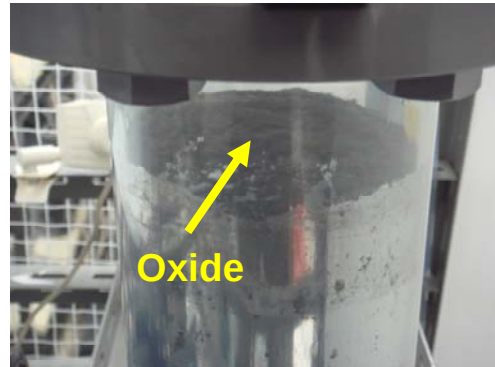


Fig. 5 Oxide generation

test section through adequate length is going to be installed in the entrance region in the future.

3.2 Operation procedures

Before starting the operation, the room temperature inside the draft should be maintained at 35 degrees C or higher. First, the inside of the piping is cleaned by using ethanol (or hydrochloric acid ethanol used for reduction). This task is important to enhance the wettability between liquid Ga and the polyvinyl-chloride pipes. Next, Ar is purged into the piping several times. Afterwards, the temperature of each piping component and the pump casing is confirmed as to whether it is around 35 degrees C. Solid gallium is melted by the band heaters wrapped around the drain tank, and then the loop is filled with liquid gallium by pressurizing the inside of the drain tank. The flow rate is gradually increased by adjusting the inverter frequency, and the residual gas inside the loop is removed. After these procedures have been taken, liquid gallium is circulated at a specified flow rate. Figure 4 shows the flow rate characteristics. On the hand, for the first operation, oxide was generated on a free surface in the upper tank as shown in Figure 5, but not any more by adjusting the oxygen concentration.

4. Conclusion

In this research, we proposed a new maintenance technology, AFCOM, to work against thermal hydraulic issues, which applies electromagnetic force in order to improve the soundness of liquid metal cooled fast reactors. Through this research, we clarified the following things: Liquid Ga is applicable as a simulant in order to realize the MHD thermal hydraulic characteristics of sodium, and liquid Ga is safe enough for use in experiments performed in a university

laboratory. Considering the wide variety of characteristics of liquid Ga, we constructed a flow test loop that used liquid Ga as the working fluid. As for future projects to obtain the specific verification examples of AFCOM, we are going to perform experiments regarding thermal fatigue induced by vortices in a fluid mixing area in a mixing tee area, and experiments for controlling flow-induced vibration caused in a low curvature bend area.

5. References

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