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Code Validation for the Behavior of Floating Absorber for Safety at Transient (FAST) under the Constant Density Condition

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1. Introduction

Innovative sodium-cooled fast reactor (iSFR) is one of SFR type reactor based on Korean Prototype Generation-IV sodium-cooled fast reactor (PGSFR). The iSFR is designed to control reactivity in the reactor core by using passive safety device which called Floating Absorber for Safety at Transient (FAST) [1]. The FAST is equipped with boron carbide so that it can insert negative reactivity into the reactor. The FAST locates normally on the outside of active core region. When an event that raises the coolant temperature occurs, buoyancy acting on the FAST decreases. Finally, the FAST falls into the active core region inserting negative reactivity. So, it is essential to analyze the behavior of the FAST to calculate inserted reactivity. Floating Absorber for Safety at Transient Analysis Code (FASTAC) has been developed to analyze and evaluate the performance of the FAST. In this study, the FASTAC validation is performed by comparing the terminal velocity of the FAST calculated by code and measured by experiment.

2. Theory

Four forces are acting on the FAST. When the reactor is in a steady-state, FAST should locate on the outside of active core region. In other words, Buoyancy acting on the FAST should be larger than gravity acting on the FAST in the steady-state. When FAST starts to fall under the transient condition, drag and pressure act on FAST in addition to buoyancy and gravity. To calculate forces acting on the FAST, velocity field around the FAST should be calculated.

2.1 Velocity Field

The fluid is assumed to be incompressible, irrotational and fully developed in the side region of the FAST (Fig 1). Velocity function (1) is derived by integrating steady-state N-S equation in cylindrical coordinate with boundary condition (2).

$$\mathrm{V_z(r)} = \frac{1}{4\mu}\frac{dP}{\mathrm{dz}}(r^2 - r_o^2) - \frac{\mathrm{V_c}+\frac{1}{4\mu}\frac{\mathrm{dP}}{\mathrm{dz}}[\mathrm{r_o^2}-\mathrm{r_i^2}]}{\ln\frac{\mathrm{r_o}}{\mathrm{r_i}}}\ln\frac{r}{\mathrm{r}_o}. \qquad (1)$$

$$\mathrm{V_z}(r_i) = V_c$$

$$V_z(r_o) = 0. \qquad (2)$$

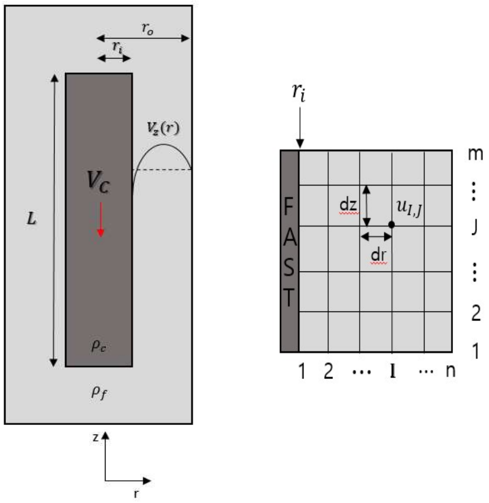

Fig. 1. Simplified schematic of the FAST and fuel pin

2.2 Buoyancy and Gravity

Buoyancy and gravity acting on the FAST can be expressed by equation (3) under the constant temperature condition.

$$\mathrm{F_g} = \rho_c \times g \times V$$

$$F_b = \rho_f \times g \times V. \qquad (3)$$

2.3 Drag and Pressure Force

It had been assumed that fluid is fully developed. According to Kim at al. the fully developed region along the cylinder length occupies about 94% of the total length of the cylinder. And the region of 6% disturbance is very small enough to be assumed fully developed for calculating wall shear stress [2]. So drag acting on the FAST is

$$F_d = \sum_{j=1}^{m-1} \mu_j \frac{u_{1,j}-u_{2,j}}{dr} dA_{side}. \qquad (4)$$

The pressure force is proportional to the pressure difference acting on both ends of the FAST.

$$F_p = \Delta P \times A_{front}. \qquad (5)$$

2.4 Calculation Process

Initially, forces acting on the FAST could be calculated with boundary condition (2). When the FAST falls, it makes the volumetric flow. The numerical analysis approach may result in a difference between the volumetric flow rate of FAST and the volumetric flow rate of FAST sideways. To reduce the difference in the volumetric flow, the pressure gradient correction process was conducted [3].

3. Experiment

A simplified experiment was conducted to ensure the validation of the FASTAC. DI water was used as a coolant instead of sodium (Fig.2). Guide wings were attached to each ends side to guide the FAST to fall in the middle of the pin. To minimize the influence of the guide wing on the behavior of FAST, they were manufactured to be less than 0.2% of the volume of FAST. When FAST reached the termination velocity, the high-speed camera recorded the time and position. The experiment was conducted for the four cases (Table. 1). To verify the validity of the FASTAC under various conditions, the differences in the density of FAST and DI water were increased.

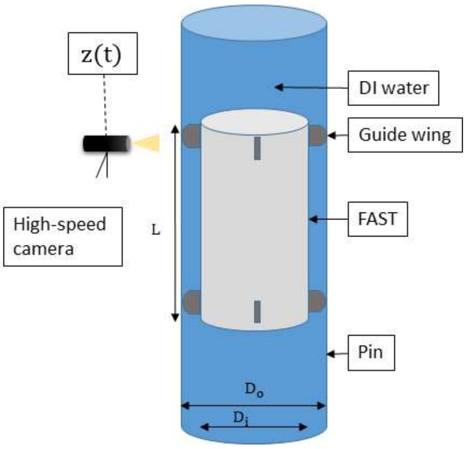

Fig. 2 Simplified experimental apparatus

Experiment	D$_i$(mm)	D$_o$(mm)	L(mm)	D$_i$/D$_o$	L/D$_o$
Case1	6.03 ±0.05	9.095±0.085	150.69±0.05	0.66	16.57
Case2	6.03 ±0.05	10.085±0.085	150.69±0.05	0.60	14.94
Case3	6.03 ±0.05	9.095±0.085	300.55±0.05	0.66	33.05
Case4	6.03 ±0.05	10.085±0.085	300.55±0.05	0.60	29.80

Table. 1. Design values of the FAST for the experiment

4. Results and Conclusion

Validation procedure of the FASTAC was conducted with the FAST terminal velocity measurement experiment under the condition that the difference in density between the FAST and DI water was in the range of $0 \sim 700 \mathrm{kg/m^3}$. The terminal velocity calculated by the FASTAC and measured by experiment were compared. The terminal velocity measured by the high-speed camera had a measurement error of about 2~3% in reading the position of the FAST. Figure 3~6 show the relative error between calculation result and experiment. The relative error value close to zero means that the calculated terminal velocity by code is almost same as measured velocity by the experiment. The relative errors do not exceed $\pm 8\%$ in all cases.

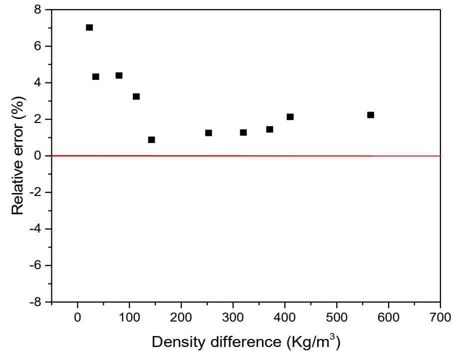

Fig. 3. Relative error vs. Density difference in case of

$$\frac{D_i}{D_o} = 0.66, \frac{L}{D_o} = 16.57$$

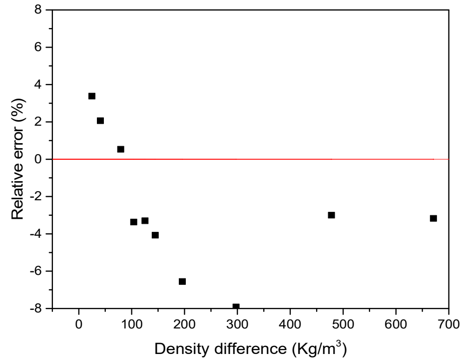

Fig. 4. Relative error vs. Density difference in case of

$$\frac{D_i}{D_o} = 0.60, \frac{L}{D_o} = 14.94$$

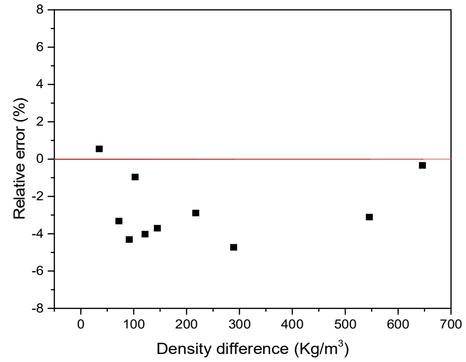

Fig. 5. Relative error vs. Density difference in case of

$$\frac{D_i}{D_o} = 0.66, \frac{L}{D_o} = 33.05$$

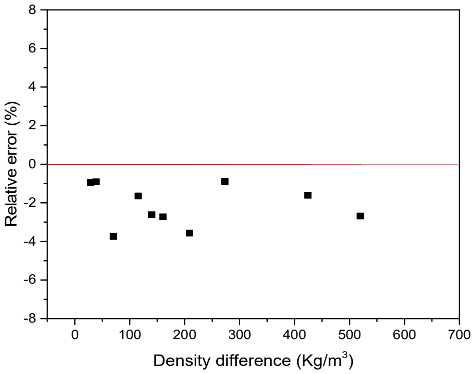

Fig. 6. Relative error vs. Density difference in case of

$$\frac{D_i}{D_o} = 0.60, \frac{L}{D_o} = 29.80$$

The reason for the biased relative errors was due to manufacturing tolerance. The reason is that manufacturing tolerances can affect the velocity field around FAST, which can cause differences in the calculation of the drag and pressure acting on FAST. Therefore, the FAST and DI water must be manufactured more precisely to reduce the relative error.

Notation

A_{front}	The front area of the FAST	$[m^2]$
A_{side}	The side area of the FAST	$[m^2]$
D_i	The diameter of the FAST	$[m]$
D_o	The diameter of the pin	$[m]$
F_b	Buoyancy	$[N]$
F_d	Drag	$[N]$
F_g	Gravity	$[N]$
F_p	Pressure force	$[N]$
g	Gravity acceleration	$[m/s^2]$
L	Length of the FAST	$[m]$
ΔP	Pressure difference	$[N/m^2]$
r_i	The radius of the FAST	$[m]$
r_o	The radius of the pin	$[m]$
$u_{I,J}$	Velocity at (I, J) node	$[m/s]$
V_c	Terminal velocity	$[m/s]$
μ	Viscosity	$[kg/m \cdot s]$
ρ_c	The density of the coolant	$[kg/m^3]$
ρ_f	The density of the FAST	$[kg/m^3]$

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