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Design of the Natural Circulation Loop and Implementation of DOWTHERM A Properties into MARS-LMR Code

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1. Introduction

For advanced nuclear reactor for a sustainable energy, the natural safety and power efficiency should be considered. Molten Salt Reactor (MSR), which is one of the generation IV reactors, has an advantage in these requirements. MSR uses a molten salt mixture as the primary coolant, or the fuel itself and it operates on high temperature, so it doesn't need pressurizing. Also, liquid state fuel has an advantage for pyro-processing with easy separation of fission products. These fission products also have relatively short half-lives compared to those of the existing reactors. With these characteristics, MSR can have inherent safety in both direct and indirect sides. Also, MSR can operate at high temperature range, so that it can have the high efficiency to produce electricity. Therefore, research of MSR is meaningful for developing advanced nuclear reactors.

FLiBe which is a mixture of lithium fluoride (LiF) and beryllium fluoride (BeF_2) is used as a primary coolant in MSR and LMR (Liquid Metal cooled Reactor). It has superiority over conventional liquid metal coolant like sodium, because it doesn't react with air or water.

In system safety analysis code, MARS-LMR, thermo- physical properties and thermodynamic tables for FLiBe is not contained. To fill the gap, experiment with thermo-physical properties generation in MARS-LMR code can contribute to the development of MSR or LMR. Since FLiBe is a noxious material, DOWTHERM A is used for the simulant material for FLiBe.

DOWTHERM A heat transfer fluid is a eutectic mixture of two very stable organic compounds, biphenyl ($C_{12}H_{10}$) and diphenyl oxide ($C_{12}H_{10}O$). Since these compounds have practically the same vapor pressures, the mixture can be handled as a single compound. Temperature range of DOWTHERM A for normal application is from 288.15K to 673.15K, and its pressure range is from atmospheric to 1.06MPa.

Because a class of heat transfer oils, at relatively low temperatures (323.15~393.15K), match the Prandtl (Pr), Reynolds (Re) and Grashof (Gr) numbers of the major liquid salts simultaneously (Bardet and Peterson 2008) [3], DOWTHERM A data between 323.15~393.15K can have similarity with FLiBe data in operating temperature range according to scaling law.

In this paper, thermo-physical properties of DOWTHERM A for MARS-LMR code will be generated using prior experimental results data from reference and code structure of the existing thermo-physical properties. In addition, natural circulation experiment apparatus was set for water and DOWTHERM A to identify heat transfer ability.

After that, experimental data will be compared to the computational data for validation.

2. Methods

2.1 Comparison of properties between FLiBe and DOWTHERM A

Table I shows the properties of FLiBe and DOWTHERM A. Though the temperature in which they have liquid phase is different, their prandtl numbers in relatively low temperature range have similar values.

Table I: Properties of FLiBe and DOWTHERM A

Properties	FLiBe	DOWTHERM A
Melting Point	733K	285.15K
Boiling Point	1703.15K	530.25K
Critical Temperature	2138.9K	770.15K
Critical Pressure	1.8MPa	3.133982MPa
Thermal Conductivity	1W/m·K	0.075W/m·K
Density	1940kg/m^3	648kg/m^3
Prandtl Number	11.7 ~ 18.6	12.8 ~16.9

2.2 Natural circulation loop

Natural circulation is the ability of a fluid to circulate continuously using gravity and changes in heat energy in a system. So, it is an important factor in nuclear reactors as one of passive safety system principles. Actually, steam generators based on natural circulation are used in PWR, PHWR, and VVER. Natural circulation is also used for cooling containment, ventilation of reactor building and reactor core cooling. It is more important after severe accident because natural circulation can remove decay heat.

Several small sized reactors like Humboldt Bay, Dodewaard and VK—50 demonstrated successfully the feasibility of operation with natural circulation as the normal mode of core cooling [6]. And many advanced reactors are designed with NC like CAREM, AHWR and ESBWR. So verifying heat transfer ability of working fluid in coolant loop by natural circulation is needed on our study. So, MSR rectangular loop was designed as shown in fig. 1 and 2. The dimension of natural circulation loop was determined considering mass flowrate following supplying heat and interval between heating and cooling sections as shown in table II. Pressure drop and mass flowrate of working fluid will be identified in this loop.

Fig. 1 shows heating and cooling sections of the experimental rectangular loop. Fig. 2 shows the whole system of experimental apparatus. Upper part consists of furnace and loop of natural circulation. Heating section 1 is the main heating area. Differently from heating section 1, heating section 2 is used for calculating mass flowrate, so its power is not high.

Fig. 3 shows the dimension of the measuring part of the loop. The maximum power is 5kW and table II shows the theoretical mass flowrate of natural circulation following each supplying heat and interval between heating and cooling sections.

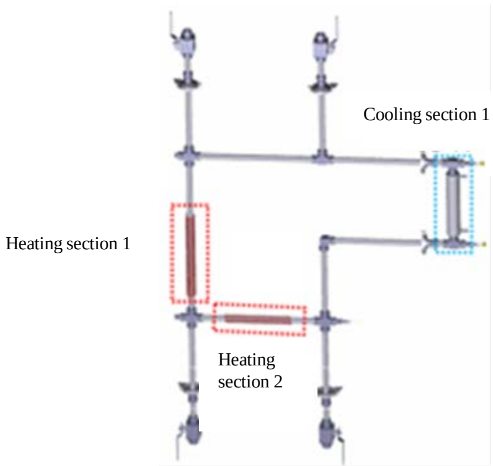

Fig. 1. Schematic of the natural circulation loop

Fig. 2. Furnace and experimental apparatus

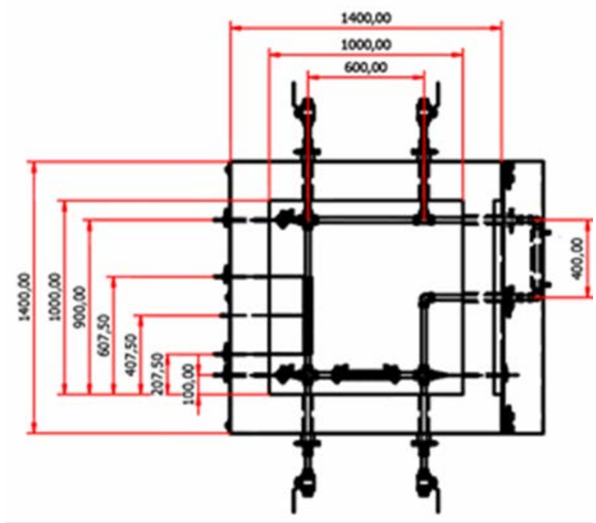

Fig. 3. Dimension of the furnace and experimental apparatus (mm)

Table II: Mass flowrate following supplying heat and interval between heating and cooling sections

Mass flowrate (g/s)		Supplying heat (Q_h)				
		1 kW	2 kW	3 kW	4 kW	5 kW
Interval Between Heating and Cooling Sections (H)	0.1 m	0.19	0.26	0.32	0.38	0.43
	0.2 m	0.26	0.38	0.46	0.53	0.6
	0.3 m	0.32	0.46	0.56	0.66	0.73

2.3 Implementation of thermo-physical properties of DOTHERM A for MARS-LMR code

Because MSR uses different fuel, coolant, core structure and other components of reactor from existing commercial reactor, its operating condition and accident phenomena are also different. So, lots of contents in MARS-LMR code have to be modified and added.

For the comparison with experimental data and contribution to thermal hydraulics simulation, thermo-physical properties of DOWTHERM A such as specific volume (m3/kg), internal energy (J/kg), thermal expansion coefficient (1/K), isothermal compressibility (1/Pa), specific heat (J/kg•K) and entropy (J/kg•K) were obtained.

Saturation equation was obtained from exponential fitting. It was divided into four parts with temperature range for more accuracy.

Formulas of thermodynamic properties for liquid and vapor phases were based on Moore [1].

2.3.1 Liquid thermodynamic properties

Liquid properties for specific volume, enthalpy, specific heat, thermal conductivity and viscosity were obtained with from Moore [1] as shown in table III. It used regression analyses with Mathcad. Normally, 5th degree polynomial is proper in fitting the data. For single phase liquid, pressure term was added.

$$property = (a + bT + cT^2 + dT^3 + eT^4 + fT^5)\left(P \cdot dd\right)^{ee} \quad (1)$$

Viscosity curve fitting used additional 3 coefficients (g = 9.433•10^{-15}, h = -5.264•10^{-18}, i = 1.275•10^{-21}) for fitting. Other liquid properties for specific volume, internal energy, thermal expansion coefficient, isothermal compressibility and entropy were calculated by following equations.

$$v_f = \frac{1}{\rho_f} \quad (2)$$

$$u_f = h_f - pv_f \quad (3)$$

$$\beta_f = \frac{1}{v_f}\left(\frac{\partial v_f}{\partial \mathrm{T}}\right)_p \quad (4)$$

$$\kappa_f = -\frac{1}{v_f}\left(\frac{\partial v_f}{\partial P}\right)_T \quad (5)$$

$$s_f = \frac{u_f + pv_f}{T} \quad (6)$$

The comparison between computed result and reference result values of liquid are shown from fig. 4 to fig. 9.

2.3.2 Vapor thermodynamic properties

Vapor properties for density, enthalpy, specific heat, thermal conductivity and viscosity were obtained with from Moore [1] as shown in table IV. It also used regression analyses with Mathcad. For single phase, temperature term was added.

$$property = (a + bP + cP^2 + dP^3 + eP^4 + fP^5)\frac{283.15}{T} \quad (7)$$

Other vapor properties for specific volume, internal energy, isothermal compressibility and entropy were calculated by following equations.

$$v_g = \frac{1}{\rho_g} \quad (8)$$

$$u_g = h_g - pv_g \quad (9)$$

$$\kappa_g = -\frac{1}{v_g}\left(\frac{\partial v_g}{\partial P}\right)_T \quad (10)$$

$$s_g = \frac{u_g + pv_g}{T} \quad (11)$$

Thermal expansion coefficient for vapor phase was calculated by exponential fitting for more accuracy.

The comparison between computed result and reference result values of vapor are shown from fig. 10 to fig. 15.

2.3.3 Transport properties

The transport properties for MARS-LMR execution file generation include viscosity (Pa•s), thermal conductivity (W/m•K) and surface tension (N/m). Viscosity and thermal conductivity were calculated from 2.3.1 and 2.3.2. Surface tension equation was obtained from three point values from DOWTHERM A catalog of Dow Chemical Company.

$$Surface\,Tension = 0.07225 - (1.1^{-4}) \cdot T \quad (12)$$

3. Conclusions

Preliminary experiment of natural circulation will be done with water. After calculating of mass flowrate with experimental data for confirming propriety of cooling, experiment with DOWTHERM A will be operated.

Also, thermos-physical properties of DOWTHERM A for MARS-LMR code were made by modifying stg file of existing one. It was based on the process of Moore [1] using 6 output parameters such as specific volume, internal energy, thermal expansion coefficient, isothermal compressibility, specific heat and entropy.

With generated stg file (stgdowa.f90) and input file, tpf file (tpfdowa) which includes fluid property tables for MARS-LMR simulation was obtained.

For the verification, this tpf file with execution file will be applied to the input deck of our natural circulation design. This work will contribute to researching and developing of MSR and LMR.

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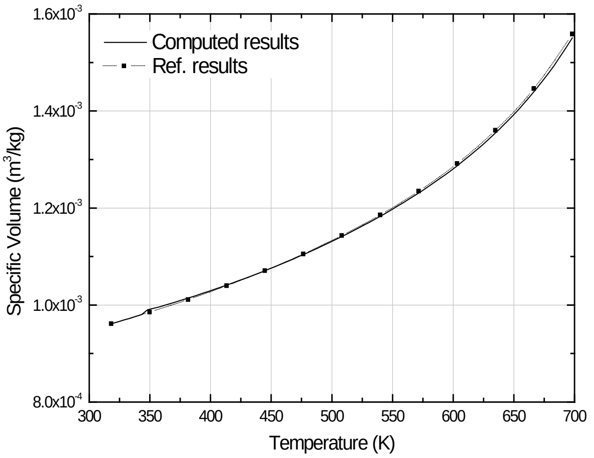

Fig. 4. Specific volume of saturated liquid

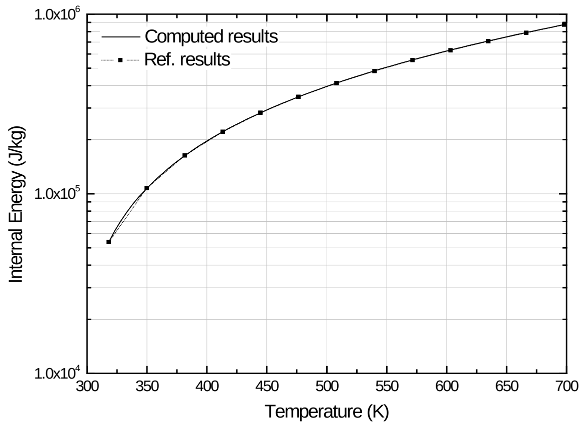

Fig. 5. Specific internal energy of saturated liquid

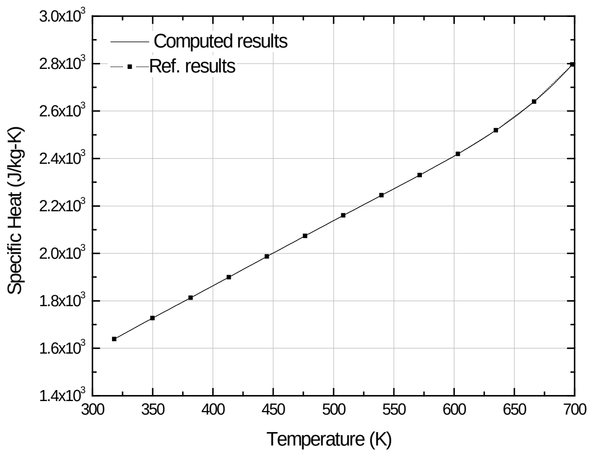

Fig. 6. Specific heat of saturated liquid

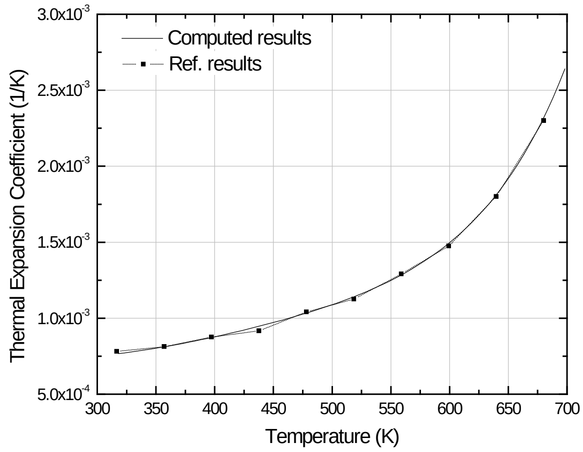

Fig. 7. Coefficient of thermal expansion of saturated liquid

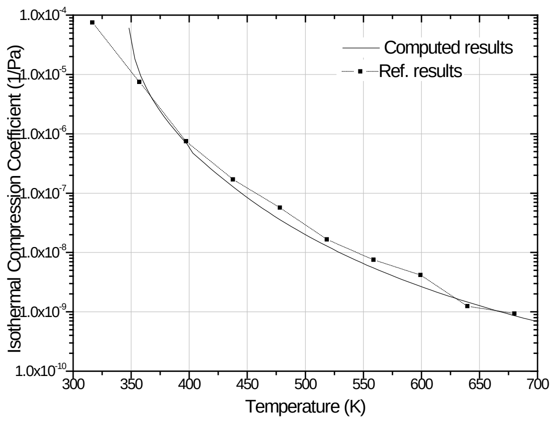

Fig. 8. Isothermal compressibility of saturated liquid

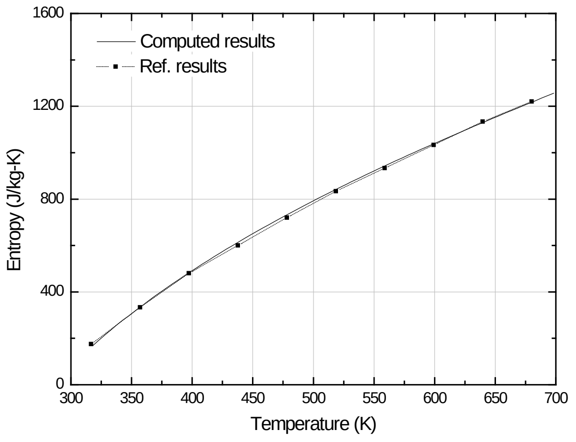

Fig. 9. Specific entropy of saturated liquid

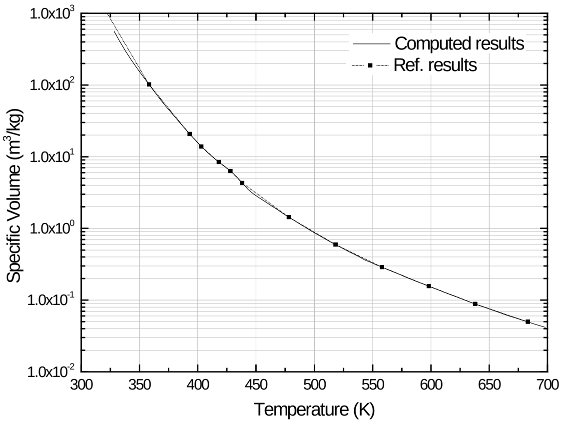

Fig. 10. Specific volume of saturated vapor

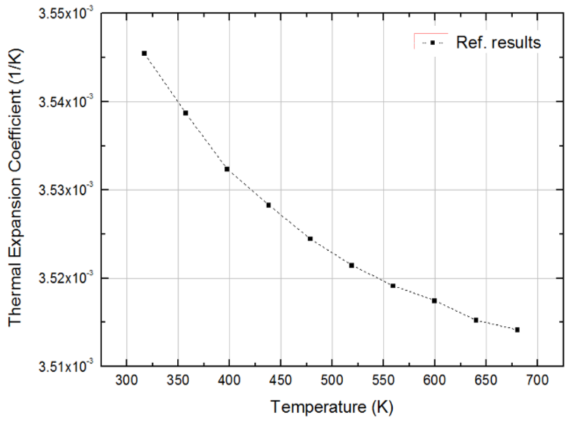

Fig. 13. Coefficient of thermal expansion of saturated vapor

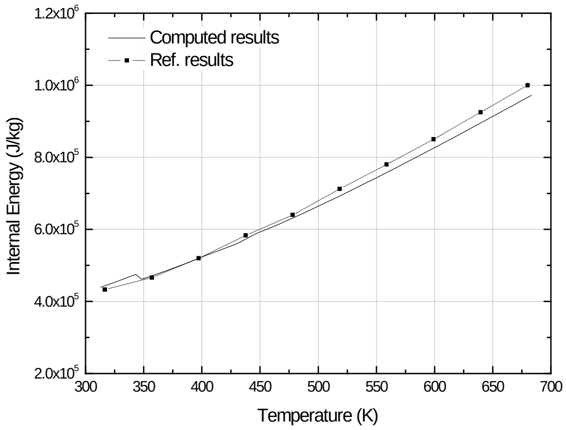

Fig. 11. Specific internal energy of saturated vapor

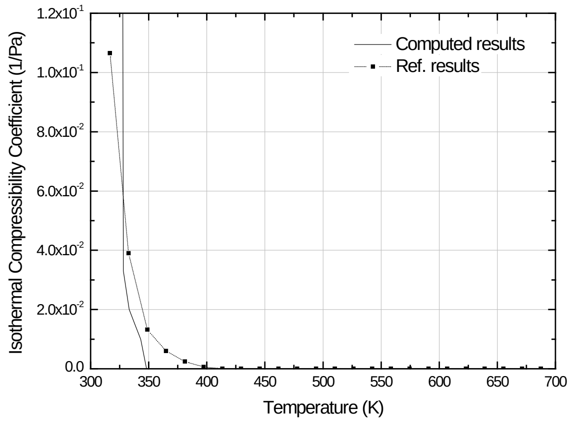

Fig. 14. Isothermal compressibility of saturated vapor

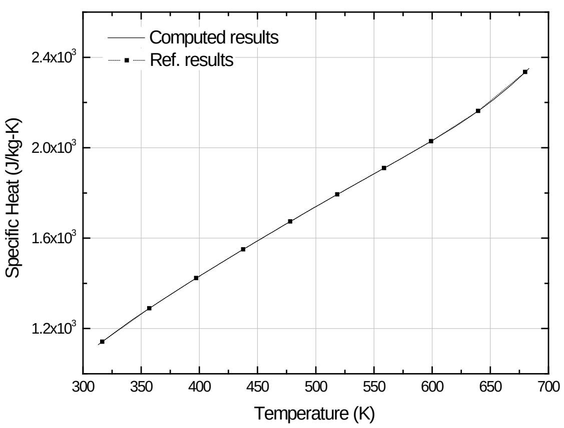

Fig. 12. Specific heat of saturated vapor

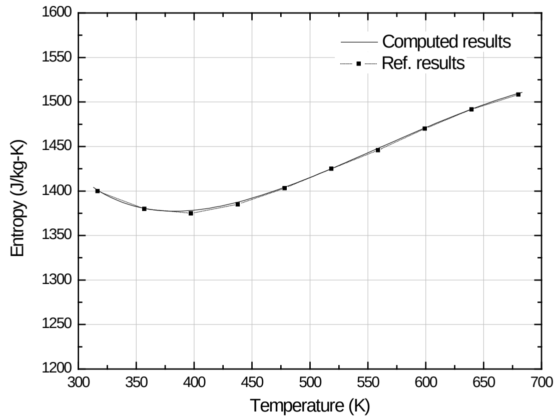

Fig. 15. Specific entropy of saturated vapor

Table III: Curve fit coefficients for liquid thermodynamic properties

Property		a	b	c	d	e	f
Saturated Liquid	Density	1.493.E+03	-3.332.E+00	1.248.E-02	-2.968.E-05	3.444.E-08	-1.622.E-11
	Enthalpy	-6.511.E+05	4.121.E+03	-1.235.E+01	2.771.E-02	-2.777.E-05	1.106.E-08
	Specific Heat	-2.364.E+03	3.946.E+01	-1.703.E-01	3.904.E-04	-4.422.E-07	1.979.E-10
	Thermal conductivity	1.856.E-01	-1.600.E-04	5.913.E-12	-	-	-
	Viscosity	5.135.E+00	-8.395.E-02	5.971.E-04	-2.409.E-06	6.029.E-09	-9.579.E-12

Table IV: Curve fit coefficients for vapor thermodynamic properties

Property		a	b	c	d	e	f	
Saturated Vapor	Density	4.391.E-05	6.119.E-05	-5.401.E-08	2.245.E-10	-5.422.E-13	5.220.E-16	$0<P\leq400$
		4.144.E-03	4.187.E-05	8.414.E-09	-3.569.E-12	4.893.E-16	-2.110.E-20	$400<P\leq11000$
		9.454.E-02	3.917.E-05	-9.340.E-12	1.696.E-17	-1.010.E-23	2.524.E-30	$P>11000$
	Enthalpy	4.004.E+05	-1.443.E+03	7.579.E+00	-1.116.E-02	1.103.E-05	-5.134.E-09	-
	Specific Heat	-5.426.E+03	6.248.E+01	-2.532.E-01	5.432.E-04	-5.842.E-07	2.508.E-10	-
	Thermal conductivity	-5.137.E-03	3.016.E-04	4.668.E-08	-	-	-	-
	Viscosity	-5.758.E-06	9.618.E-08	-4.013.E-10	-1.011.E-12	-1.249.E-15	6.114.E-19	-