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Eung Soo Kim
Piyush Sabharwall
Nolan Anderson

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Eung Soo Kim*, Piyush Sabharwall, and Nolan Anderson
Idaho National Laboratory, P.O. Box 1625, Idaho Falls, ID 83415-3890, EungSoo.Kim@inl.gov

INTRODUCTION

The high temperature nuclear reactor based on either helium or fluoride-based molten salt primary coolant are currently envisioned as promising future reactor concepts because of their high efficiency, safety, and process application capabilities [1, 2]. In these types of reactors, an intermediate heat transfer loop (IHTL) is an essential part for achieving high reactor efficiency and economics. The IHTL consists of various heat exchangers, circulators, and pipe systems, and it transfers heat from the reactor primary to the power conversion and process application systems. Currently, the IHTL is considered very important in the advanced system designs, and its performance is highly dependent on selection of the coolants.

This paper mainly focuses on characterization and selection of the IHTL coolants. Basically, gases, liquid metals, molten salts are possible coolant options. The following lists some general characteristics required for the IHTL coolant:

- **High heat transfer performance**: The IHTL coolant should exhibit high heat transfer performance to achieve high efficiency and economics.
- **Low pumping power**: The IHTL coolant requires low pumping power to improve economics through less stringent pump requirements.
- **Low amount of coolant volume**: The IHTL coolant requires less coolant volume for better economics.
- **Low amount of structural materials**: The IHTL coolant requires less structural material volume for better economics.
- **Low heat loss**: The IHTL requires less heat loss for high efficiency.
- **Low temperature drop**: The IHTL should allow less temperature drop for high efficiency.

Typically, heat transfer coolants are selected based on various fluid properties such as melting point, vapor pressure, density, thermal conductivity, heat capacity, viscosity, and coolant chemistry. However, the selection process & results are highly dependent on the engineer's personal experience and skills.

In the coolant selection, if a certain coolant shows superior properties with respect to the others, the decision will be very straightforward. However, generally, each coolant material exhibits good characteristics for some properties but poor for the others. Therefore, it will be very useful to have some figures of merits (FOMs), which can represent and quantify various coolant thermal performances in the system of interest. The study summarized in this paper focuses on developing general FOMs for the IHTL coolant selection and shows some estimation results.

DEVELOPMENT OF FIGURE OF MERITS (FOMS) FOR IHTL COOLANT SELECTION

Figure 1 shows the basic configuration of the general intermediate heat transfer loop. Heat (*Q*) is transferred to the coolant system via heat exchangers, heater, burners, etc. with increase of coolant temperature. This coolant is driven by pumps or circulators to transport the heat to several locations for use in electricity generation, chemical process, etc. Therefore, operating temperature and pressure of this system are generally determined and optimized by types of energy usages. However, detailed heat transfer performance, system size, and major component specifications are significantly affected by types of coolants.

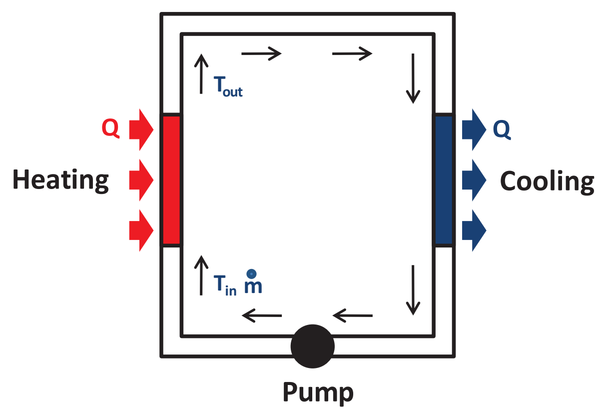

Figure 1. General configuration of intermediate heat transfer loop.

With the six requirements mentioned above, six figures of merit (FOMs) were developed in this study. Because of the page limits, the derivations of the FOMs are not presented in the paper but will be presented in the conference. The following summarizes the FOMs and their physical meanings:

1) **FOM_{ht}**: This FOM represents the heat transfer performance of the coolant. It measures the heat

transfer rate per unit pumping power for a given geometry.

2) **FOM$_p$**: This FOM represents the pumping power of the coolant. It measures the pumping power required to transport the same energy for a given geometry.
3) **FOM$_{cv}$**: This FOM represents the volume of the coolant. It measures the coolant volume required for transferring heat with the same heat and pumping power.
4) **FOM$_{ccv}$**: This FOM represents the volume of the structural materials. It measures the volume of the coolant structural materials required for transferring heat with the same heat duty and pumping power under given operating conditions (T and P).
5) **FOM$_{hl}$**: This FOM represents the heat loss of the coolant. It measures the heat loss of the coolant when it is transported to the same distance with the same heat duty and pumping power.
6) **FOM$_{dt}$**: This FOM represents the heat loss of the coolant. It measures the temperature drop of the coolant when it is transported to the same distance with the same heat duty and pumping power.

Table 1. Summary of FOMs for IHTL Coolants.

Figure of Merits	Sensitivity of Properties				
	S_k	S_ρ	S_{Cp}	S_μ	S_P
Heat transfer performance factor (*FOM$_{ht}$*): $FOM_{ht} = \frac{(k)^{0.6} \cdot (\rho)^{0.58} \cdot (C_p)^{0.4} \cdot (\mu)^{-0.47}}{R_{ht,0}}$	0.6	0.58	0.4	-0.47	0.0
Pumping factor (*FOM$_p$*): $FOM_p = \frac{\rho^{-2} \cdot C_P^{-2.8} \cdot \mu^{0.2}}{R_{p,0}}$	0.0	-2	-2.8	0.2	0.0
Coolant volume factor (*FOM$_{cv}$*): $FOM_{cv} = \frac{(\rho)^{-0.84} \cdot (C_p)^{-1.16} \cdot (\mu)^{0.1}}{R_{cv,0}}$	0.0	-0.84	-1.16	0.1	0.0
Material Volume factor (*FOM$_{ccv}$*): $FOM_{ccv} = \frac{(P) \cdot (\rho)^{-0.84} \cdot (C_p)^{-1.16} \cdot (\mu)^{0.1}}{R_{ccv,0}}$	0.0	-0.84	-1.16	0.1	1.0
Heat loss factor (*FOM$_{hl}$*): $FOM_{hl} = \frac{(k)^{0.6} \cdot (\rho)^{0.34} \cdot (C_p)^{0.06} \cdot (\mu)^{-0.44}}{R_{hl,0}}$	0.6	0.34	0.06	-0.44	0.0
Temperature drop factor (*FOM$_{dt}$*): $FOM_{dt} = \frac{(k)^{0.6} \cdot (\rho)^{0.34} \cdot (C_p)^{0.06} \cdot (\mu)^{-0.44}}{R_{dt,0}}$	0.6	0.34	0.06	-0.44	0.0

Table 1 summarizes all the FOMs derived and proposed for the IHTL coolants. Based on the FOMs summarized, heat transfer performance, pumping power, coolant volume, pipe material volume, coolant heat loss, and coolant temperature drop can be compared easily and quantitatively for the same heat duty and pumping power requirements. Plus (+) sign of a sensitivity indicates that the FOM increases with the properties while minus (-) sign indicates that the FOM decreases with the properties. This table also shows the sensitivity of the FOMs in terms of various fluid properties. The sensitivities of the FOMs were estimated by the following formula:

$$S_\varphi = \frac{\partial FOM / FOM}{\partial \varphi / \varphi} \qquad (1)$$

The numbers of the sensitivities shows that how much the FOMs are affected by each property. If the sensitivity is higher, the FOM is more significantly affected by that property. From this table, the effects of properties on the thermal-hydraulic performance of the coolants can be interpreted as follows:

- Increasing thermal conductivity can increase heat transfer performance by a power of 0.6, but it also increases heat loss and temperature drop of the coolant at the same rate.
- Increasing coolant density can increase heat transfer performance and reduce coolant volume by powers of 0.58 and 0.84 respectively. It also decreases pumping power by a power of 2.
- Increasing heat capacity can increase heat transfer performance and significantly reduce coolant/material volume by powers of 0.4 and 1.16 respectively with decreases of pumping power. On the other hand, increase in heat loss and temperature drop are negligible (= 0.06).
- Increasing viscosity increases pumping power and coolant volume with significant reduction in heat transfer performance.

Table 2 shows the comparisons of the thermal-hydraulic characteristics of the various coolants based on the estimated FOMs. In this estimation, the water at 25°C and 0.1 MPa was selected to be the reference coolant. The following summarizes the results:

- ***FOM$_{th}$***: Higher *FOM$_{th}$* is preferred for better heat transfer performance. According to the comparisons, Sodium shows the highest value (=19.05) and Ar has the lowest value (0.05). Overall, FOM$_{th}$ is the highest in liquid metal followed by liquid water, molten salt, and gases, respectively.
- ***FOM$_p$***: Lower *FOM$_p$* is preferred for better efficiency and economics. According to the comparisons, liquid water has the lowest value (=1.0) and Ar has the highest value (=72592). Overall, *FOM$_p$* is the lowest in molten salt followed by liquid metal and gases, respectively.

- ***FOM**$_{cv}$*: Lower FOM$_{cv}$ is preferred because it requires less coolant volume for providing the same amount of heat transfer performance under the same pumping power. According to the comparisons, the liquid water has the lowest value (=1.0) and Ar has the highest (=101.44). Overall, FOMcv is the lowest in molten salt followed by liquid metal and gases, respectively.
- ***FOM**$_{ccv}$*: Lower FOM_{ccv} is preferred because it requires less structural material volume for both heat transfer pipes and components. Overall, the same result was obtained as the FOM_{cv}. The FOM$_{ccv}$ is the lowest in molten salt followed by liquid metal and gases, respectively.
- ***FOM**$_{hl}$*: Lower FOM$_{hl}$ is preferred because it requires less insulation for preventing heat loss. According to the comparisons, Ar has the lowest value (=0.2), and sodium has the highest (28.9). Overall, the FOM_{hl} is the lowest in gases followed by molten salt and liquid metal, respectively.
- ***FOM**$_{dt}$*: Lower FOM$_{hl}$ is preferred because it requires less insulation for preventing heat loss. Exactly the same results were obtained for the FOM_{dt} compared to the FOM_{hl}.

Table 2. Comparisons of FOMs for various coolants.

	Coolant	FOM$_{th}$	FOM$_p$	FOM$_{cv}$	FOM$_{ccv}$	FOM$_{hl}$	FOM$_{dl}$
Ref.	Water (25C, 1 atm)*	1.00	1.00	1.00	1.00	1.00	1.00
Gas (700°C, 7 MPa)	He	0.12	25407.41	67.74	4741.80	0.40	0.40
	Air	0.07	40096.15	80.10	5607.14	0.26	0.26
	CO_2	0.11	11390.17	47.19	3303.46	0.32	0.32
	H_2O (Steam)	0.11	10012.63	45.10	3157.12	0.32	0.32
	Ar	0.05	72592.09	101.44	7100.53	0.20	0.20
Molten Salt (700°C)	LiF-NaF-KF	0.80	2.87	1.57	1.57	0.92	0.92
	NaF-ZrF_4	0.45	5.02	1.98	1.98	0.56	0.56
	KF-ZrF_4	0.38	8.69	2.49	2.49	0.51	0.51
	LiF-NaF-ZrF_4	0.40	5.36	2.05	2.05	0.50	0.50
	LiCl-KCl	0.55	14.99	3.07	3.07	0.76	0.76
	LiCl-RbCl	0.47	23.03	3.66	3.66	0.70	0.70
	NaCl-$MgCl_2$	0.58	16.26	3.18	3.18	0.81	0.81
	KCl-$MgCl_2$	0.50	14.30	3.02	3.02	0.70	0.70
	NaF-$NaBF_4$	0.71	5.66	2.04	2.04	0.88	0.88
	KF-KBF_4	0.64	8.98	2.47	2.47	0.84	0.84
	RbF-RbF_4	0.54	14.61	3.01	3.01	0.75	0.75
Liquid Metal (700°C)	Sodium	19.05	33.62	4.19	4.19	28.91	28.91
	Lead	6.05	111.64	6.90	6.90	10.82	10.82
	Bismuth	6.61	100.69	6.60	6.60	11.66	11.66
	Lead-Bismuth	4.86	142.94	7.65	7.65	8.95	8.95

CONCLUSIONS

Figure of Merits (FOMs) were developed in this study for the IHTL coolant characterization and selection. Totally, six FOMs were developed and they covered (1) heat transfer performance, (2) pumping power, (3) coolant volume, (4) structural material volume, (5) heat loss, and (6) temperature drop. Sensitivity of various coolant properties on the FOMs were also estimated here. In this sensitivity analysis, importance of each property was quantified. Finally, various coolants were compared based on the developed FOMs. The FOMs developed in this study are expected to significantly contribute IHTL coolant selection in the future high temperature nuclear reactor designs and they will be also widely applied to the general heat transfer component design & configuration study.

NOMENCLATURE

k	= thermal conductivity
μ	= viscosity,
ρ	= density,
C_p	= heat capacity.
φ	= any property (k, μ, ρ, C_p)
FOM_{th}	= figure of merit for heat transfer performance
FOM_{th}	= figure of merit for pumping power
FOM_{cv}	= figure of merit for coolant volume
FOM_{ccv}	= figure of merit for pipe structure volume
FOM_{hl}	= figure of merit for heat loss
FOM_{dt}	= figure of merit for temperature drop
$R_{ht,0}$	= reference value for FOM_{th}
$R_{p,0}$	= reference value for FOM_p
$R_{cv,0}$	= reference value for FOM_{cv}
$R_{ccv,0}$	= reference value for FOM_{ccv}
$R_{hl,0}$	= reference value for FOM_{hl}
$R_{dt,0}$	= reference value for FOM_{dt}
S_φ	= sensitivity of FOM for a property, φ

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