Heat Loss Simulation and Uncertainty Analysis in Fuel Bundle CHF and Other Large Scale Thermal-Hydraulic Experiments

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ABSTRACT

Heat transfer experiments play a key role in exploring the underlining mechanisms of nuclear reactor thermal hydraulic phenomena. Large scale heat transfer tests, especially for rod bundle critical heat flux (CHF) experiments, generally utilize high power to achieve necessary operation conditions including wide ranges of temperature, flow, pressure, etc.. Temperature differences between test boundary, the boarding equipment, secondary flow housing, and the surrounding environment can be significant. Besides, heavy mass components, such as flanges, housing, and adaptor, can also serve as large heat sinks or heat sources leading to potentially large heat loss/gain and measurement uncertainty. Due to the complication of the installation and coupling of thermal-hydraulic conditions between inner and outer flow paths, direct measurement of heat loss/heat gain often becomes very difficult or nearly impossible. Furthermore, if there is a secondary layer of isolation fluid with potential natural circulation under various transient and steady operations, the total heat loss could have rather complicated dependency on operating conditions. When the total heating power is measured, reliable heat loss estimation is essential for accurate experimental measurements.

As for a large scale test facility, different scales, experimental configurations, and operating conditions might lead to different heat loss. This paper presents a case example of heat loss/gain for a high pressure fuel assembly CHF test facility. In this CHF test loop, the test section consists of an inner flow path with an outer surrounding chamber filled with stagnant coolant that might present a significant source of heat loss/heat gain resulting from natural circulation in the surrounding chamber. System code RELAP 5 is used to simulate the test section and the surrounding systems under typical CHF test conditions. The simulated results are further compared to experimental data to verify the model's feasibility.

KEYWORDS

Temperature difference, heat loss, heat transfer tests, RELAP 5

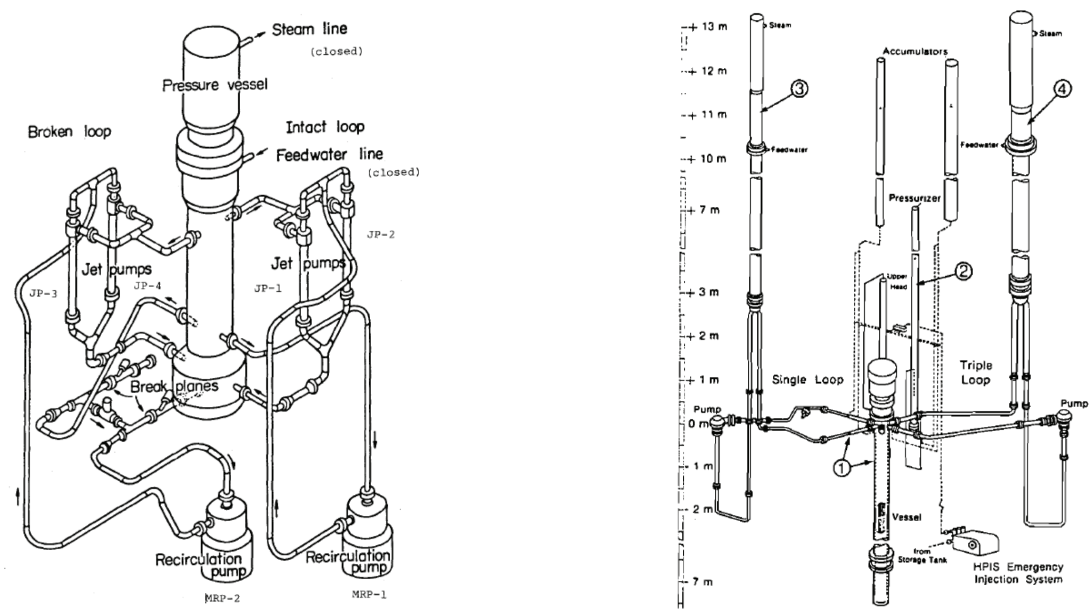
1. INTRODUCTION

Heat transfer experiments act as one of the major ways to explore the mechanisms of nuclear reactor thermal hydraulic phenomena. For large scale heat transfer tests such as rod bundle critical heat flux (CHF) experiments, high heating power is generally applied to achieve the assumed operation conditions for high temperature, high flow rate, high pressure etc. Some components in these test facilities, appear to be a potential source of significant heat loss/gain. The temperature difference existing in adjacent components including test boundary, the boarding equipment, secondary flow housing, or the surrounding environment and test flow channel causes heat transfer and conduction, which result in the heat loss/heat gain during the experiments. For some certain operation conditions, the temperature difference can be so enormous that leads to a significant heat loss/gain. Thus, heat loss/gain can be an important parameter that directly affects the measurement and data analysis, particularly for transient operation.

Studies on heat loss/gain are limited in reactor thermal-hydraulic experiment. The ROSA-III program (1981)[1] conducted by JAERI was one of the earliest program exploring heat loss. Built as a loop type, ROSA-III test facility was for investigating the loss-of-coolant-accident (LOCA) of BWR/6, as illustrated in **Figure 1-A**. ROSA-III analyzed the heat loss at the steady state and summarized a simple relation between the net heat loss rate and the temperature difference between an average fluid temperature in the system and the room temperature. J. Sanders (1991)[2] proposed three methods on steady state, heat-up and cool-down, cool-down heat loss measurement separately. The basic model is

$$C\dot{T} = P - HL \tag{1}$$

While the heat capacity, C, includes the fluid, the metal wall structures, and the heated proportion of the insulation material. It is assumed that the temperature of the facility is represented by the change of temperature - $\dot{T} = dT/dt$. These methods were applied to the measurement system in the LOBI facility, which was built as 1:712 PWR for safety experimental research, as shown in **Figure 1-B.**



A - ROSA-III test loop **B - LOBI test facility**

Figure 1 Heat loss test facilities

For ROSA-III and LOBI test facilities, the heat loss in experiments only occurs in the heat transfer between test loop and surrounding environment. The heat loss mainly relates with temperature difference and thermal insulation between test section and surrounding environment [1, 2]. However, as for CHF experiments, the unique design of the flow channel test section (**Figure 2**-typical CHF test section schematic diagram) and outer chamber with stagnant water brings about new issues. Due to the temperature difference and potential natural circulation in the outer chamber, the water in the outer chamber can potentially impact the heat loss or heat gain significantly on the test section. The condition of the water in the outer chamber can also influence the time span from one condition to steady state after an operation change. For CHF test, CHF data measured under unsteady state can be non-conservative if the actual heat loss to the outer chamber is not properly accounted for. However, most recent large scale rod bundle CHF tests were performed without paying much attention to heat loss measurement, which may lead to mistake in CHF measurement. In CHF test and data analysis, the CHF or heat flux calculation uses the total heating power. In calculation, the heat loss/gain is not removed from total power or added to the total power. Hence, the uncertainty of CHF/heat flux is produced. The CHF uncertainty γ_{HL} caused by the heat loss/gain is closely related with the total heat loss/gain and total loss/gain rate. Generally, the higher heat loss/gain rate, the larger of γ_{HL}. The heat loss rate is defined as:

$$HL\ rate = \frac{HL}{P} \times 100\% \tag{2}$$

where *P* is the total heating power.

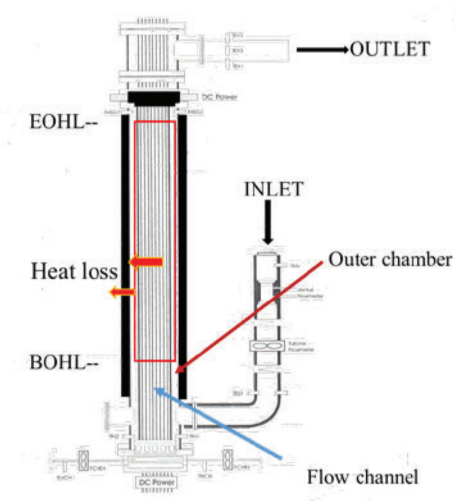


Figure 2 Typical CHF test section

In this paper, the system code RELAP5-MOD3.3 was applied to simulate the transient condition in a typical rod bundle CHF test facility shown in **Figure 2** as prototype. The test bundle consists of 6×6 heating rod equipped with 10 spacer/mixing grids.

2. HEAT LOSS OF TYPICAL CHF TEST FACILITY SIMULATION

For CHF tests, due to the complication of the installation and coupling of thermal-hydraulic conditions between inner and outer flow paths, direct measurement of heat loss/heat gain often becomes very difficult or nearly impossible. CHF data measured is compiled of every single CHF data without the transition between any two points. To obtain the transient phenomena, system code RELAP 5 is employed to simulate the transient in condition transition.

After collecting a set of CHF data, the system pressure, mass velocity, power, inlet temperature will be adjusted to another condition to obtain new data. The surrounding out of test section is set under room temperature as 25°C. Thus, the flow channel temperature at one elevation appears to be a little higher than that of outer chamber while outer chamber's temperature is higher than room temperature. The temperature difference between flow channel and outer chamber results in heat loss; on the other hand, when conditions change from a relative high pressure high temperature-HPHT (in flow chamber) steady state to a low pressure low temperature steady state, the flow temperature can be lower than that of the outer chamber at previous steady state. The heat is transferred from outer chamber to flow chamber resulting in heat gain.

2.1. RELAP Model For Heat Loss Simulation

The original RELAP5 computer code has been developed by the Idaho National Engineering Laboratory (The RELAP5 Code Development Team, 2001)[3]. This is a one-dimensional non-equilibrium two-phase thermal–hydraulic system code. This RELAP5 code has been successfully applied to PWR thermal-hydraulic analysis. To obtain the needed transient process, RELAP code or CFD code can be used to simulate. Comparing to CFD, the RELAP code has several advantages in heat loss/gain simulation, including easy to set up model and less time and computational consuming. Besides, the RELAP 5 code can provide sufficient accuracy in simulating, as shown in **Table 1.**

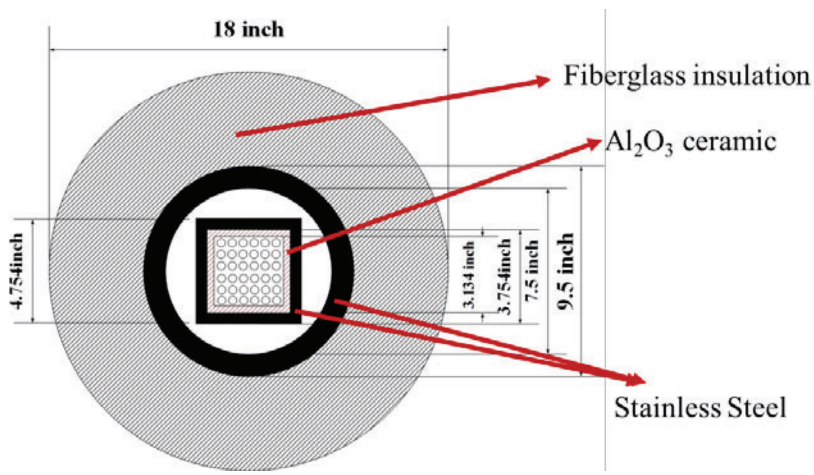


Figure 3 Cross Section of typical CHF test section

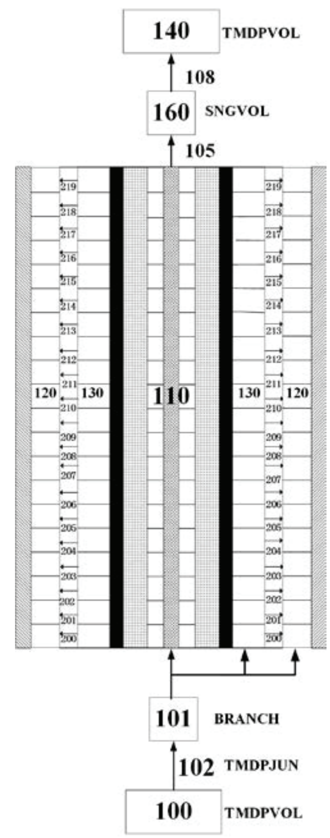


Figure 4 RELAP Model for Heat Loss Simulation

The cross section of typical CHF test section geometry and material is illustrated as **Figure 3**. The exit pressure P_{ex}, and exit temperature T_{ex} are measured at the end of heat length (EOHL in **Figure 2)**. The RELAP simulation model is shown as **Figure 4.** Pipe 110 represents the test flow channel. The outer chamber is divided into two same area components annulus 120 and 130. Components 110, 120 and 130 are divided into 20 control volumes in vertical direction. Single junctions 200 to 219 connect the 130-01 with 120-01 to 130-20 with 120-20. The mass flow in 200 to 219 show the intensity and direction of natural circulation between 120 and 130 in outer chamber. Time dependent volumes 100 and 140 define the inlet temperature and exit pressure to set up the boundary conditions. Time dependent junction 102 provides the inlet mass flow. All the heat transfer from 110 to 130 is taken as heat loss; all the heat transfer from 130 to

110 is taken as heat gain. For all simulations, the conditions including mass velocity, pressure, heating power, initial temperature totally derive from practical operation.

For the same power, inlet/exit pressure and temperature from the RELAP simulation steady state, the result should be equal to the experimental data. **Table 1** depicts that the simulation result and experimental data agrees very well.

Table 1 Comparison between RELAP 5 result and experimental data

CASE NO.	T_{ex}/K	$T_{top-120}$/K	Pressure drop/kPa	
Case 1	616.5	604.3	148.3	Simulation Result
	616.7	604.6	148.4	Experimental Data
Case 2	597.0	598.2	161.9	Simulation Result
	597.1	598.0	162.0	Experimental Data

2.2. Natural Circulation Transient In Outer Chamber

When condition changed from a relative low pressure low temperature (LPLT) steady state to a high pressure high temperature steady state (in flow chamber), the flow temperature can be higher than it was at previous steady state. The temperature difference between flow channel and outer chamber grow much larger than it was at steady state. Especially for cooled down condition (close to room temperature) heating up, the temperature difference can be very large so that the water temperature at the bottom of the outer chamber promptly increases as the test section inlet temperature increases. When being heated up, the expansion of water in outer chamber induce a upper to bottom flow. Besides at the very beginning, water temperature at the bottom can be higher than the middle's or top's. These two effects introduce a natural circulation in outer chamber with a direction of in-side-out. The continued natural circulation will gradually reduce the temperature gradient between the top and the bottom of the outer chamber, which in turn will reduce the natural circulation flow, and eventually/gradually reach another steady state.

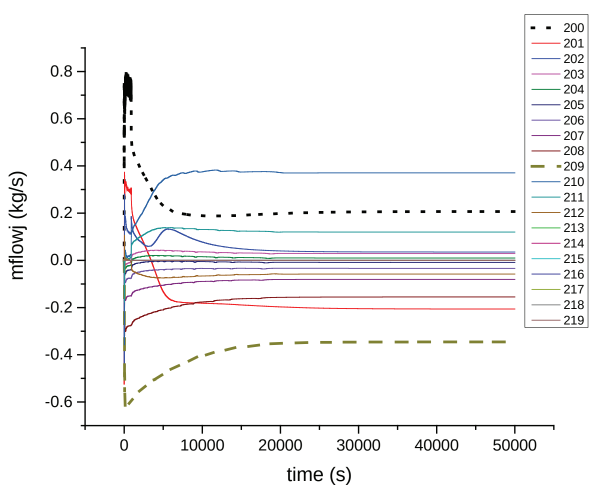


Figure 5 Natural Circulation in heat loss transient

Conditions for simulating the heat loss in **Figure 5** are summarized in **Table 2**. As shown in **Figure 5,** control volumes 200, 201, 202 etc. depict negative mass flow meaning there exists a lateral flow from 120 to 130 while 209, 210, 211,212, etc. show positive mass flow from 130 to 120, presenting an in-side-out natural circulation in outer chamber. The largest circulation flow reaches to 0.77kg/s, and 213 to 219 appears to have no flow. It shows that the density difference induced driving force is not large enough to drive the whole outer chamber to circulate. The natural circulation can mix the stagnant water up, increasing the heat transfer between flow channel and outer chamber.

Table 2 Simulation condition of Natural Circulation in heat loss transient

Condition parameter	Value
Initial loop temperature	299.2K
Inlet temperature T_{in}	535.8K
Exit pressure	17.18MPa
Heating power	7176.2kW

On the other hand, when conditions change from a very high pressure high temperature steady state to a low pressure low temperature steady state, the flow temperature can be much lower than that of the water in outer chamber. The water inside of outer chamber (i. e. volume 130 side) is cooled by the flow channel water, while outside remains hot. Thus, density difference introduces a natural circulation in outer chamber from outside to inside.

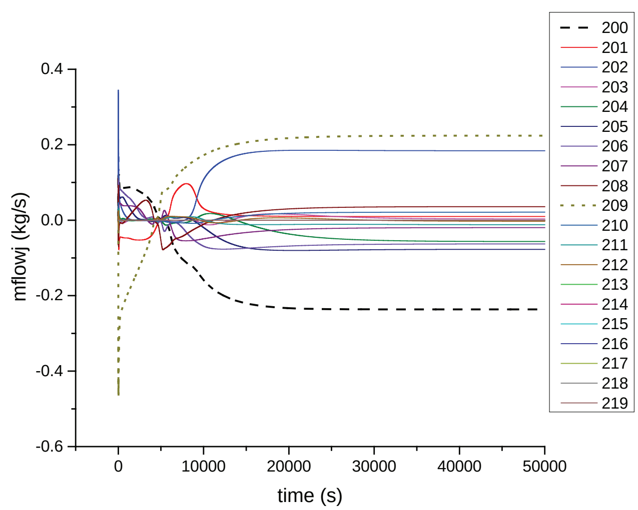


Figure 6 Natural Circulation in heat gain and loss transient

Table 3 Condition of Natural Circulation in heat gain transient

Condition parameter	Value
Initial outer chamber temperature	544.95 - 594.25K(bottom to top uniformly)
Inlet temperature T_{in}	479.85K
Exit pressure	15.34MPa
Heating power	1615.45kW

Table 4 Temperature trend of three volume

Volume number	11020	13020	12020
Time/s	T_{ex}/K	$T_{top-130}$/K	$T_{top-120}$/K
4185	525.96	526.51	526.53
4477	525.94	525.94	525.89
5256	525.91	523.06	522.93

Conditions for simulating the heat gain in **Figure 6** are summarized in **Table 3**. As shown in **Figure 6,** control volume 200, 201, 202 etc. depict positive mass flow meaning there exists a lateral flow flows from 130 to 120 while 209, 210, 211,212, etc. generate negative mass flow from 120 to 130, showing an out-side-in natural circulation in the outer chamber. The largest circulation flow reaches to 0.47kg/s, and213 to 219 appears to have no flow as well. After about 5000s, the flow in 200, 201, 202 to 212 all reverse direction. Looking into the temperature of the direction transition point (**Table 4**), the Tex is lower than $T_{top-130}$ at 4185s and turns to be equal at 4477s and finally becomes higher. The temperature difference between flow channel and outer chamber changes from negative to positive, inducing the reverse of circulation.

2.3. Heat Loss/Gain Simulation

Heat loss/gains measurement in CHF test can not be conducted owing to the high pressure test section and complicated installation for CHF data collection and the cost for fabrication. Thus, heat loss simulation for transients utilizes RELAP5 code. To verify the simulation feasibility, key parameters such as pressure and temperature, are compared to steady state experiment data at the same condition.

To evaluate the heat loss/gain, several simulations of heat loss/gain of different conditions are conducted. Largest heat gain, heat loss, and a steady state transition between two close conditions are selected in these cases. The results of the three case are shown in **Figure 7, Figure 8** and **Figure 9**.

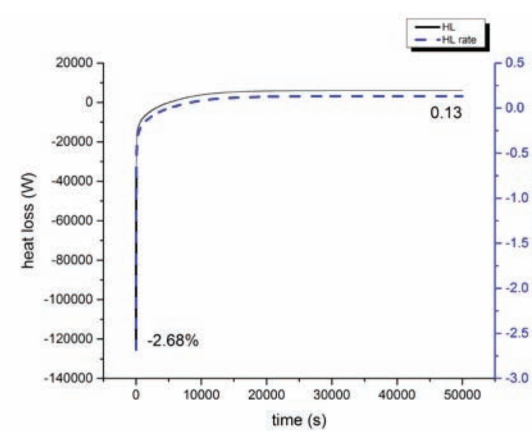


Figure 7 Largest Heat Gain result

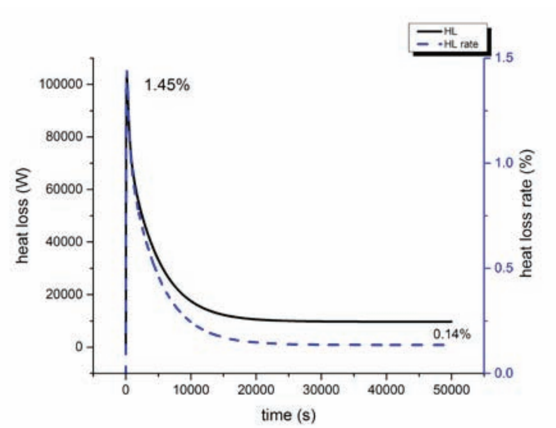


Figure 8 Largest Heat Loss result

Figure 7 depicts the largest heat gain in simulation reaching 2.68%, which may be encountered in high pressure high temperature conditions adjusting to low pressure low temperature. **Figure 8** shows the largest heat loss in simulation reaching 1.45%, which may be present in cold condition adjusting to high pressure high temperature. **Figure 9** reveals the relative low temperature condition adjusting to higher temperature condition. 2.68% and 1.45% heat loss/gain rate is very significant in data analysis. On the contrary, the heat loss/gain rate under steady state is generally lower than 0.2%, which is negligible in measurement. Thus, when collecting CHF data, steady state should be reached to avoid the large heat loss/gain state.

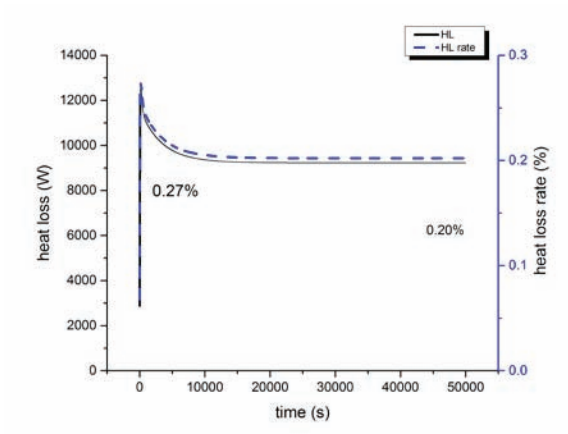


Figure 9 Normal condition change heat loss result

2.4. Time To Reach Steady State

During any experimental testing with such large scale facility, it is critical to examine the parameter trends of all key components to assure the steady status of the system prior to the recording of the data. Otherwise, the heat loss or heat gain could become a major source of measurement uncertainty.

As shown in the diagram, the volume 120-20 locates at the top of 120 and outside of outer chamber, thus becoming last to reach steady state. The time to reach steady state is the time that temperature $T_{top\text{-}120}$ reaches 99%/101% of steady state. Eight cases' results are depicted in **Table 5**.

Table 5 Time to reach steady state of different condition

Time to reach peak heat loss (s)	Peak heat loss ratio/%	Time to reach SS (s)	SS heat loss ratio/%
310	0.56	10842	0.19
326	0.61	15962	0.16
271	0.63	17082	0.16
248	0.61	16722	0.14
234	0.62	17670	0.13
22	1.51	18048	0.15
168	1.45	18110	0.14

For high heat loss/gain condition, time to reach steady state (T_{ss}) is generally longer than small condition changes of small heat loss/gain. As shown in the above table, T_{ss} spread over a wide range from few minutes to many hours. All data should be collected under steady state to minimize any measurement uncertainty..

3. KEY FACTORS OF HEAT LOSS/GAIN ANALYSIS

For flow in test section, the energy balance is expressed by heat generation Q (heating rods' power), the heat loss HL (negative value representing heat gain), the increasing energy of flow Q_f. The heat loss is given as

$$HL = Q\text{-}Q_f \tag{3}$$

Q generally maintains constant in a data collecting cycle. Q_f is affected by key parameters of flow including temperature T, system pressure P, mass velocity G and etc.. Besides, outer chamber cools /heats the flow in flow channel exerting a significant effect on flow. Thus, the water temperature in chamber appears to be another important factor to heat loss analysis. However, due to the few measuring points, data of key parameters is limited to flow inlet and exit pressure of P_{in} and P_{ex}, flow inlet and exit temperature of T_{in} and T_{ex}, water temperature at top of outer chamber T_{ch}, main flow mass velocity G.

As shown in **Table 6**, heat loss from outer chamber to surrounding is much smaller than that of heat loss from flow channel to outer chamber at peak heat loss. While for steady state, the heat loss from outer chamber to surrounding occupies much more than half of heat loss from flow channel to outer chamber. Thus, the governing factors are different for these two conditions. At transient conditions as peak heat loss, the significant cold source of outer chamber dominates the heat loss process. Key parameters of flow channel and outer chamber condition impact the heat transfer from flow channel to outer chamber. As for the steady state, the heat transfer from outer chamber to surrounding plays a key role in total heat loss.

Table 6 Peak HL and Steady State HL

Case NO.	Peak HL-110	Peak HL-surrounding	SS HL-110	SS HL-surrounding
1	26496.4	100.32	8851.6	5806.9
2	35717.6	110.33	9518.9	6245.7
3	40477.0	57.44	9184.0	6255.7
4	39782.5	43.94	9051.5	6198.4

3.1. Heat Loss Trend Over Key Parameters In Condition Transition

In condition transition, the exit pressure, mass flow, inlet and exit temperature generally change to new condition rapidly. On the contrary, the temperature change in outer chamber is very slow due to the slow heat conduction between flow channel and outer chamber. As shown in **Figure 10**, the heat loss generally does not show any consistency with Pex, Tex, ΔT_{EI}. Reversely, the heat loss almost share the same trend with ΔTec. This represents that the temperature difference between flow channel and outer chamber governs the heat loss/gain process. The mass flow nearly maintains constant through the whole process. In the other condition transition process, heat loss over these five parameters shows the similar trend.

3.2. Key Factors of Heat Loss/Gain At Transient

For heat loss transient conditions, the temperatures in flow channel and outer chamber as well as the temperature difference between them vary with time. Increasing/decreasing of mass flow or inlet temperatures between two steady state results in heat loss/gain fluctuation. Conditions reaching the peak of heat loss in these fluctuations are selected to analyze the parameter trend. The trends are revealed in **Figure 11**, where the ΔT_{EC} represents the temperature difference between T_{ex} and $T_{top-120}$ and the ΔT_{EI} represents the temperature difference between T_{ex} and T_{in}.

As shown in **Figure 11-A,** the heat loss generally increases with T_{EX}. For **Figure 11-B**, the heat loss generally increases with the increasing of G. For **Figure 11-C**, the heat loss generally increases with the ΔT_{EC} which is the temperature difference between flow channel and outer chamber. For **Figure 11-D,** the heat loss generally increases with ΔT_{EI}. For CHF test, the exit flow of test section reaches saturation governing by P_{ex}. Hence, in **Figure 11-E**, it shows the similar trend with **Figure 11-A,** but the effect is very weak. For **Figure 11-B**, data points at about 2700kg/m^2.s are scattering. For these points, the T_{ex}, P and G of them are very close. The different heating power induces different subcooling length (the length between flow channel inlet and where bulk flow reaching saturation). Thus, the subcooling length (**L_{sub}**) is introduced to explain the disorder. **Figure 11-F** shows the decreasing of heat loss with larger **L_{sub}** of the scattering points.

3.3. Key Factors of Heat Loss/Gain At Steady State

For heat loss steady state conditions, all the parameters become steady. Plenty of heat loss cases are simulated and the results are presented in **Figure 12**.

As shown in **Figure 12-A,** the heat loss generally increases with the higher T_{EX}. The similar trend also appears in **Figure 12-B**. For **Figure 12-C**, most points appear in scattering. **Figure 12-D,** the heat loss generally decreases with the increasing of ΔT_{EI}. For In **Figure 12-E**, the trend of heat loss over G shows scattering overall. Trend over **L_{sub}** is same with that at peak heat loss condition in **Figure 12-F**.

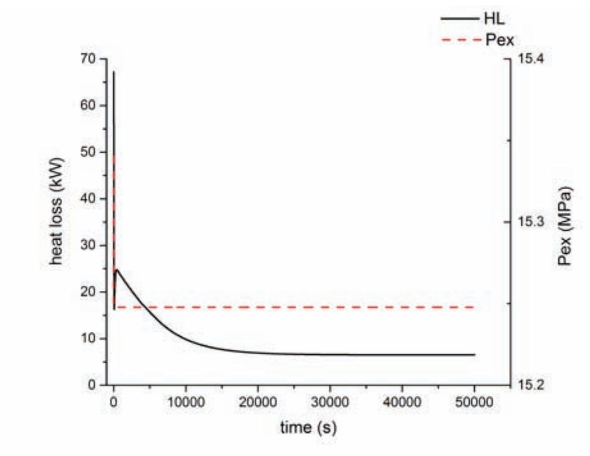
To reduce the L_{sub} and temperature effect, the points are selected under close temperature and L_{sub} in **Figure 13**. The trend reveals that heat loss decreases with increasing G at steady state.

4. CONCLUSIONS

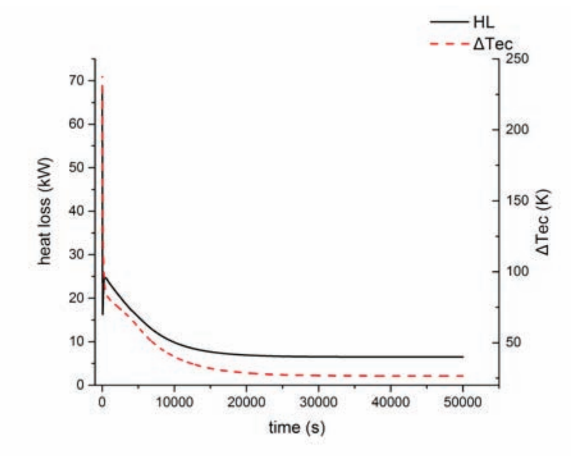
This paper focuses on the heat loss issues in CHF test. The outer chamber around test section with heavy mass introduces much larger heat capacity and can result in greater heat loss/gain, which was never encountered in other thermal-hydraulic experiment. Furthermore, the complex installation of CHF test severely restricts the measurement of heat loss/gain. However, RELAP5 code with limited data simulates the transient condition with sufficient convenience and shows good agreement.

A. RELAP code serves as a quick heat loss/gain simulation tool with sufficient speed and accuracy.
B. Heat loss/gain appears to be significant in some conditions in CHF test; steady state should be reached when collecting CHF data to avoid large heat loss/gain.
C. Few measurements like temperature in outer chamber should be considered to equip for heat loss/gain monitoring.
D. For heat loss in transient and steady state condition, the different dominant heat transfer process leads to different level of heat loss/gain and different influencing parameters.

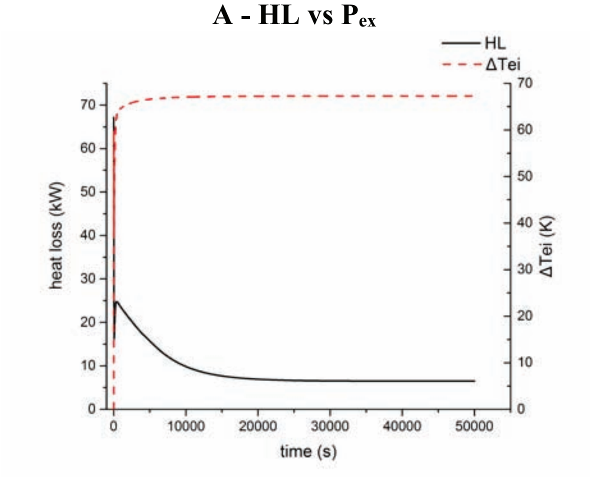
Cases analyzed in this paper are mostly not severe cases for heat loss study due to large heating power required for the 6x6 bundle. For a 5x5 bundle or smaller bundle (4x4), the total heat lost could be much more significant, especially with low flow, high temperature, high inlet subcool cases. Furthermore, the outer chamber size is larger for small bundle, which may lead to larger heat loss/gain and time span to reach steady state, for different scale rod bundle generally sharing the same test pressure-bearing housing. The pressure-bearing housing size and bundle scale effect on heat loss/gain will be further explored then.



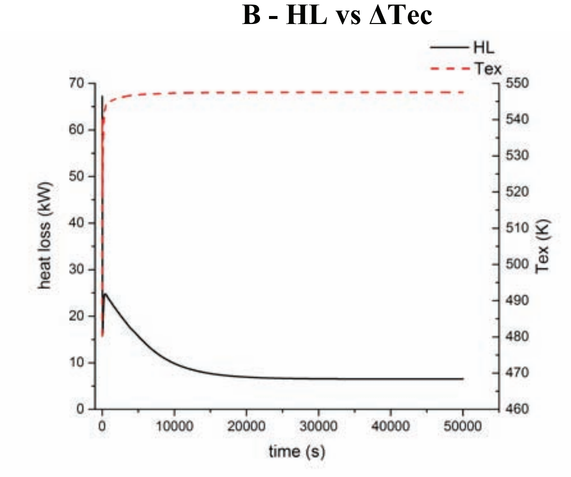
A - HL vs P_{ex}



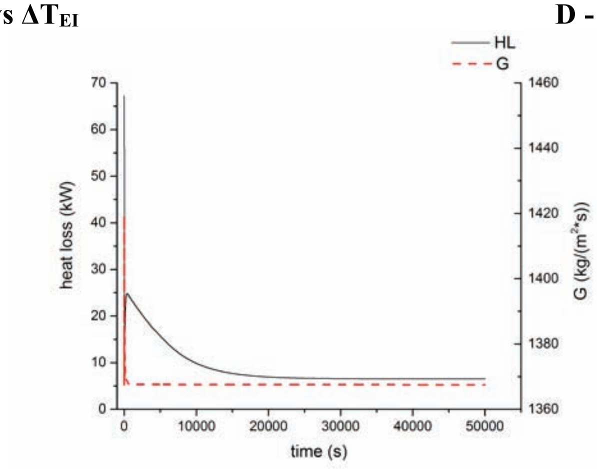
B - HL vs ΔTec



C - HL vs ΔT_{EI}

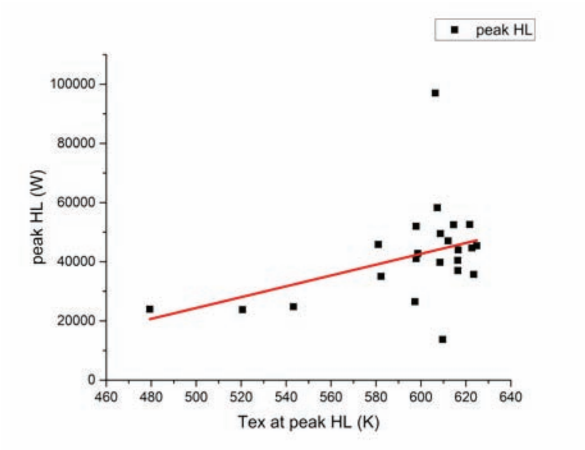


D - HL vs T_{ex}

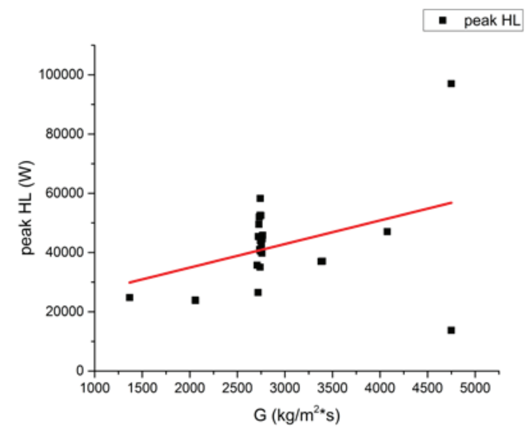


E - HL vs G

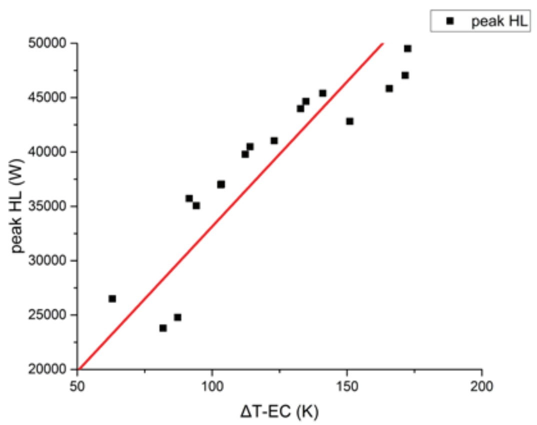
Figure 10 HL VS key parameters in transient



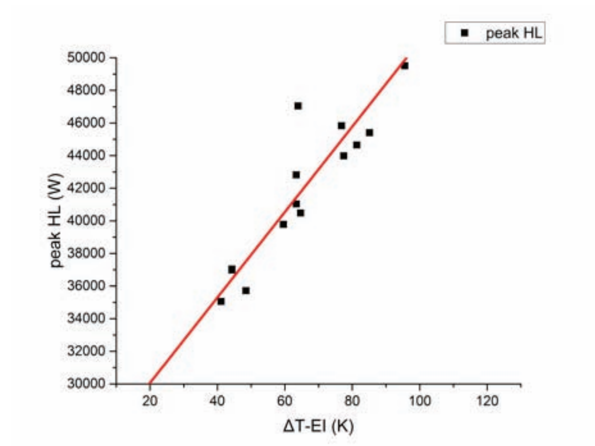
A - HL vs T_{ex}



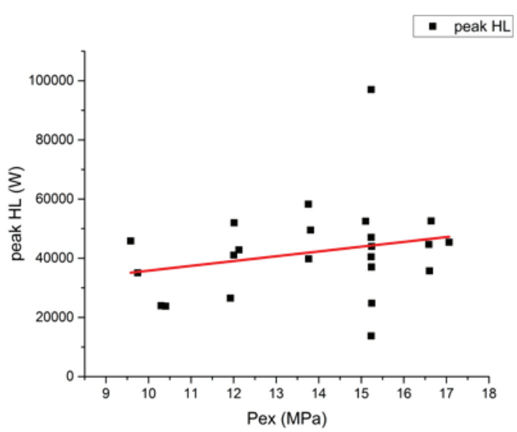
B - HL vs G



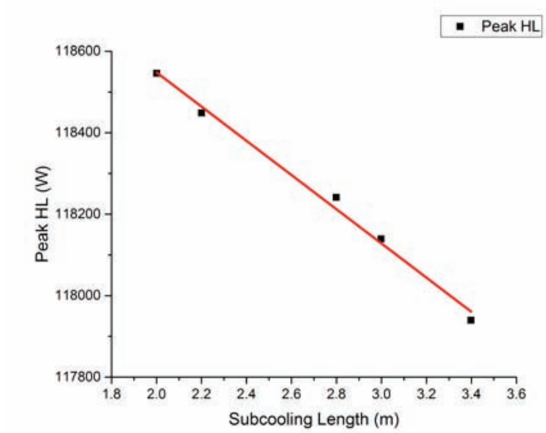
C - HL vs ΔT_{EC}



D - HL vs ΔT_{EI}

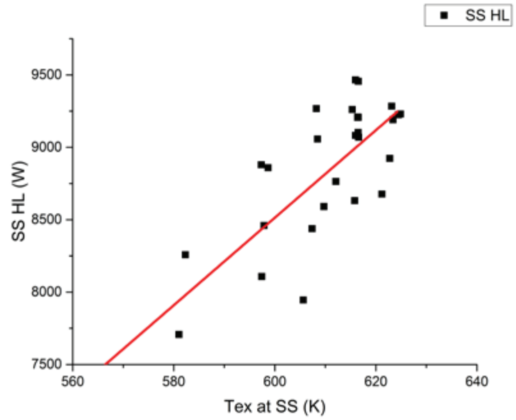


E - HL vs P_{ex}

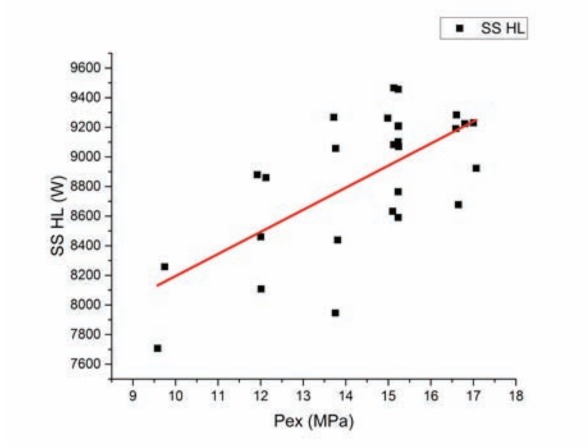


F - HL vs L_{sub}

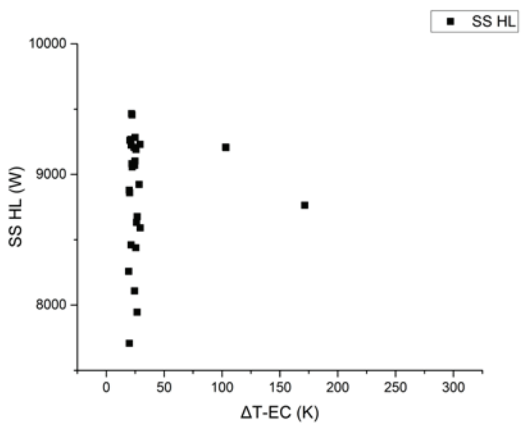
Figure 11 Parameter trend analysis of heat loss transient



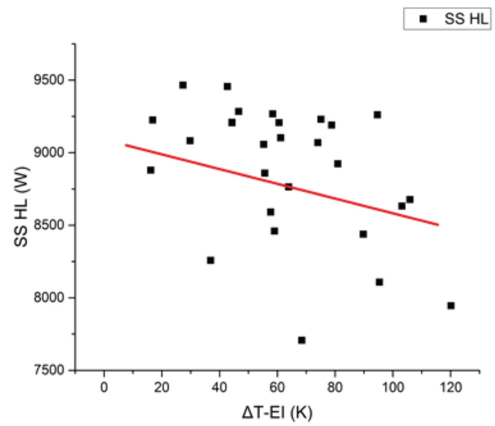
A - HL vs T_{ex}



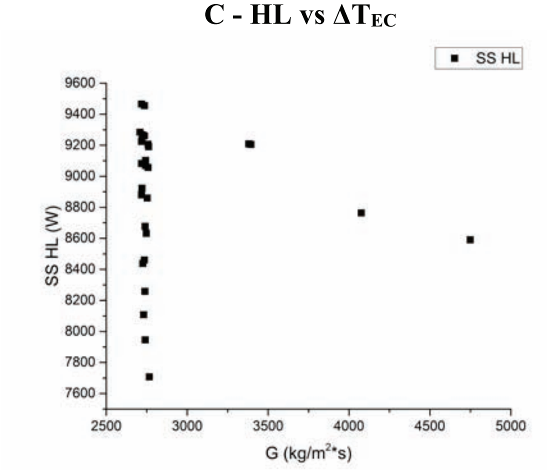
B - HL vs P_{ex}



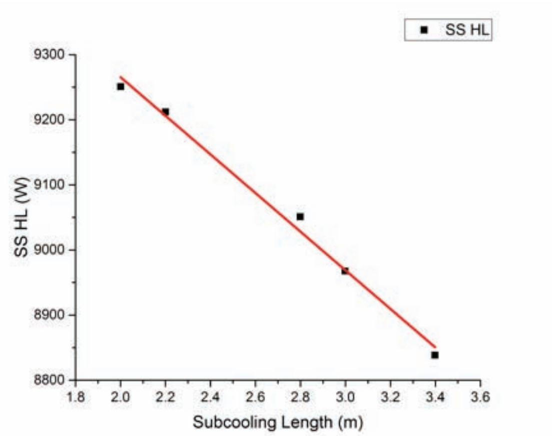
C - HL vs ΔT_{EC}



D - HL vs ΔT_{EI}



E - HL vs G



F - HL vs L_{sub}

Figure 12 Parameter trend analysis of heat loss steady state

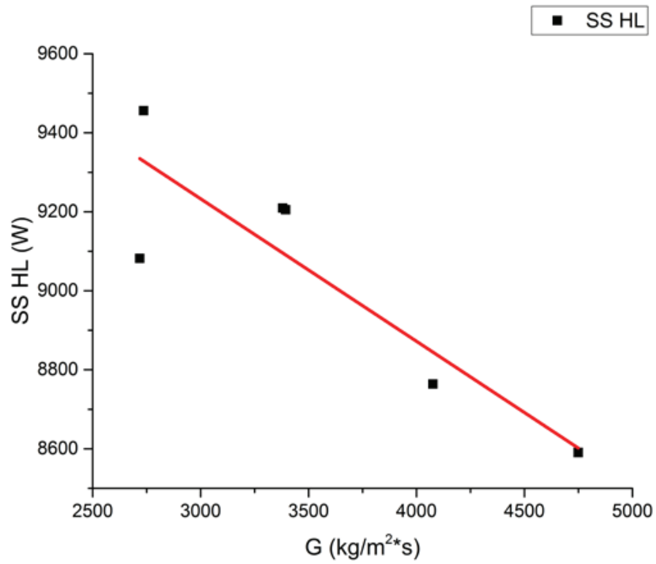


Figure 13 HL vs G at different close conditions

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