HEAT LOSS EVALUATION IN LARGE SCALE ROD BUNDLE CHF EXPERIMENTS

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ABSTRACT

An assessment is performed using experimental data as well as RELAP and CFD modeling to evaluate the potential rate of heat loss in large scale thermal-hydraulic experiments. In particular, the most common sources of heat loss are identified for a typical rod bundle Critical Heat Flux (CHF) experiment setup involving a rectangular geometry (4x4, 5x5, or 6x6) PWR experimental condition or other hexagonal geometry (19 or 37 fuel bundle). The quantitative appraisal for typical rate of heat loss is summarized for one of the identified potential source of heat loss, through the test housing defining the main thermal-hydraulic boundary of the entire test bundle. The simulation results from RELAP and CFD simulation were carried. The results are drawn and some recommendations are presented in this paper for the proper accountability of heat loss in performing large scale thermal-hydraulic experiments.

KEYWORDS
Heat loss; large scale bundle test; CFX; RELAP

1. INTRODUCTION

During the performing of PWR rod bundle CHF experiments, there are many potential issues which might have major impact on the test results in term of overall CHF, the standard deviation and measurement uncertainty of the CHF measurement. Among these potential issues, some of them might be easily identified (such as excessive rod bow, cold rod CHF, mid-span CHF, etc.)[1-2], however, some issues might not be so obvious and can be a hidden error for any uncertainty analysis and have fatal impacts on the accuracy and repeatability of the measurement, which in turn will affect the reliability of any conclusion, correlation, or prediction, as well as design limit for safety analysis application[3-4]. Some examples of potential hidden challenges include but not limited to excessive and unidentified heat loss, inaccurate measurement without redundant measurements, undetectable bypass flow (gasket open and close after cool down), undetectable bundle title, non-representative Thermal hydraulics conditions (such as excessive or non-representative quenching at exist of test section which minimize flow instability phenomena which will otherwise lead to early PFI/CHF phenomena, especially at steam line break conditions, etc[5].

Among many factors, accurate measurement, calculation, prediction, and accountability for the heat loss is one of the most critical requirement in obtaining reliable and accurate measurement in thermal or thermal-hydraulic experimental systems. This type of assessment can be extremely challenging especially for a very small scale, nano-scale, where an accurate measurement is extremely difficult due to the challenging operation in a quantitative measurement of such small quantity amount, or an extremely large scale heat transfer or thermal –hydraulic experimental setting where the heat loss measurement become very complicated and challenging due to the complexity of the measurement system as well as the difficulty involved in handling high pressure, high temperature, fast transient, complicated systems with wide range of operating conditions from extremely high pressure, high flow, high power (under high subcooled conditions) to extremely low pressure, low flow, high quality, and low heat flux conditions. [5-6] For the large scale rod bundle CHF experiments for Light Water Reactor (LWR), especially the Pressurized Water Reactor (PWR), the percentage of heat loss become a very challenging issue and often overlooked especially in establishing a new test facility. Since the total heat loss of any experimental setup is depending on not only test components, the test setting, experimental scales (both temporal and spatial), it is also often depending on the experimental approach, it is critically important for a new facility to carefully examine, investigate, and develop its own heat loss assessment as a functions of all the key parameters in order to fully benchmark the new facility and satisfy all the validation, verification, and uncertainty qualification (VV/UQ) requirements in order to provide quality rod bundle CHF data.

2. THE HEAT LOSS IN THE TESTING FACILITY

2.1. Typical Experimental Set-up and Potential Sources of Heat Loss for a Rod Bundle CHF Testing Facility

As shown in the Figure 1, a typical large scale rod bundle CHF experimental facility usually utilizes a main test loop consisting of major components such as test section, heat generation systems (power supply), heat rejection system (exchangers, etc.), mixer, pump, pressurizer, water treatment system (on-line), main circulation system (pumps), as well as instrumentation and control system[7]. Unlike BWR rod bundle CHF testing and other large scale thermal-hydraulic testing, due to the complexity of the geometry, the lack of analytical solution, the high heat flux, high pressure, and high temperature, as well as the broad range of operating/testing conditions (from extreme subcooled fast transient DNB to high quality/void dryout, etc.), the rod bundle PWR CHF testing is a rather challenging task[8].

Due to the complexity resulting from the coupling effects among various elements and physical phenomena, including but not limited to thermal, hydraulic, electrical, force balance, geometry constraint, and measurement difficulty, as well as its complicated dependency on various operating factors, it is rather difficult to positively identify and quantify the total heat loss of a large scale thermal hydraulic CHF experimental facility.

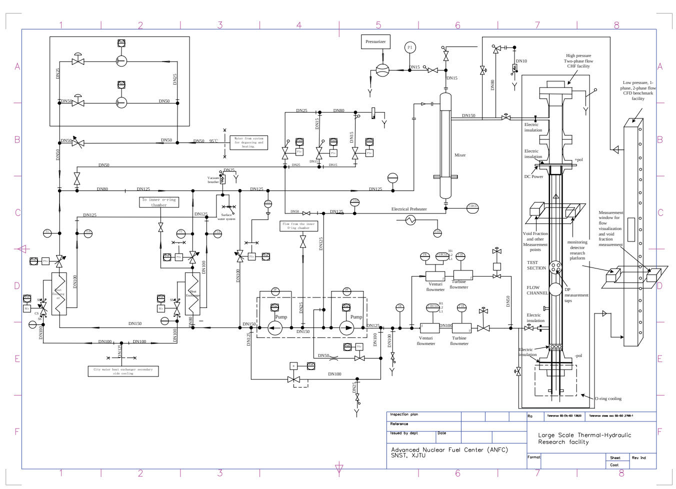

Figure 1 Typical Experimental Set-up for a Rod Bundle CHF Testing Facility

As shown in the Figure 2, the potential sources of heat loss include but not limited to heat loss through bottom of the cooling chamber (direct bypass or excessive or under cooling), the heat loss through excessive rod leakage, heat loss/or heat gain through various components that are not within measurement boundary (such as bottom or top end pieces), heat loss through hydraulic boundary, namely the test housing (or called shroud box) boundary, etc.   The key source involved complicated flow fields and heat transfer mechanism as well as various speed transient conditions. The detailed information can be obtained on Figure 3 which shows the 3D views and illustrates the heat loss mechanism. The test section is surrounded in a square box which has three layers to support the strength and thermal insulation. The coolant is injected from the annulus between the outer and inner chamber.

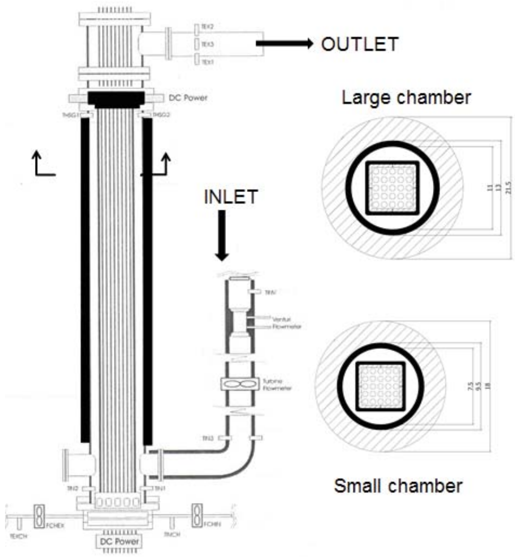

Figure 2 Typical Experimental Set-up with Potential Sources of Heat Loss

Table Ⅰ The parameters of the facility

Geometry	Inner chamber	Square side length	in	2.56
	Ceramic wall	Square side length	in	3.18
	Steel wall 1	Square side length	in	4.18
	Outer chamber	Diameter	in	7.5 in small chamber
				11 in large chamber
	Steel wall 2	Diameter	in	18 in small chamber
				21.5 in large chamber

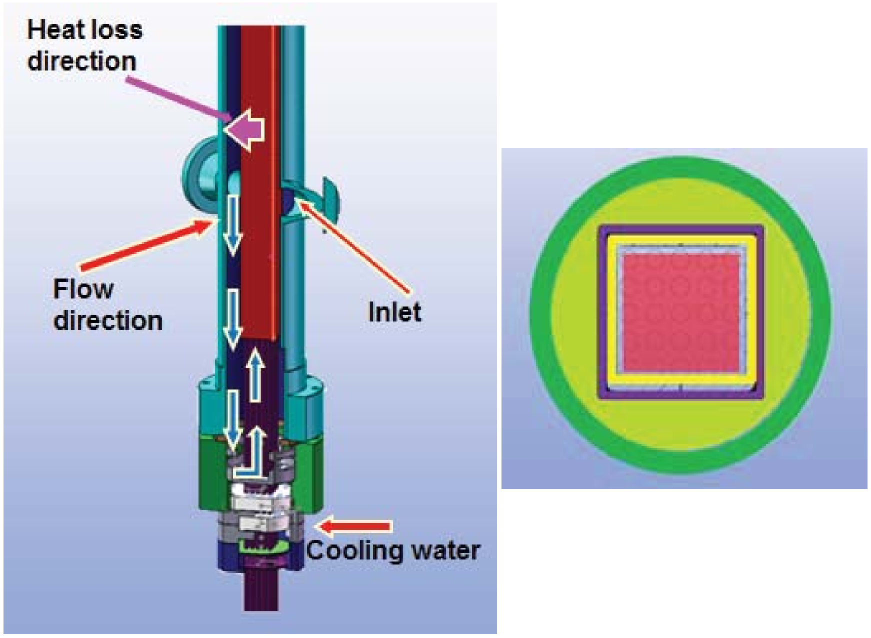

Figure 3 The sketch map of heat loss in the experiment

In this paper, to obtain the law of the heat loss in the experiment, four cases will be analyzed to cover different conditions. The operating conditions are listed in Table Ⅱ which covered the typical condition in the experiment. In the beginning of test, the temperature in the channel is almost same as the environment, so the temperature distribution from the top of the outer chamber to the inlet is considered varying from 30 ^{o}C to the coolant temperature. After some test cases, the temperature in the outer chamber should be equal to the test one. In that case if the test condition changed, the temperature distribution should vary from the last case to the inlet temperature as shown in case 3.

Table Ⅱ The operating conditions to analyze

case1 (large chamber)	T inlet	^{o}C	310
	T outer chamber initial	^{o}C	30 ^{o}C
	System pressure	MPa	18
	Flow rate	kg/s	5
	Initial power	MW	0.46
	Rate of power change	MW/minutes	0
case2 (small chamber)	T inlet	^{o}C	310
	T outer chamber initial	^{o}C	30 ^{o}C
	System pressure	MPa	18
	Flow rate	kg/s	5
	Initial power	MW	0.46
	Rate of power change	MW/minutes	0
	T inlet	^{o}C	120

case3 (large chamber)	T outer chamber initial	^{o}C	310 ^{o}C
	System pressure	MPa	18
	Flow rate	kg/s	5
	Initial power	MW	0.46
	Rate of power change	MW/minutes	0
case4 (small chamber)	T inlet	^{o}C	120
	T outer chamber initial	^{o}C	310 ^{o}C
	System pressure	MPa	18
	Flow rate	kg/s	5
	Initial power	MW	0.46
	Rate of power change	MW/minutes	0

2.2 Calculation model

To obtain the heat losses in the experiment, the accurate calculation should be taken. In the nuclear engineering, the system code which is simple and fast and the CFD code which is accurate and much time consuming are popular ones, so the RELAP5 code and CFX code were selected to analyze the cases.

2.2.1 CFD- CFX Modeling and Heat Loss Assessment

To obtain the detailed information, the popular CFD code CFX which used popular in the nuclear engineering is employed. Four simulation cases as shown in Table 2 were calculated and analyzed. To get the accurate results, the transit process is adopted and the mesh is examined before.

a). Case 1: in this case, the large chamber is used and the fluid domain is divided to total 811,989 mesh elements. Temperature distribution in the outer chamber was set initial from the top of outer chamber to the near inlet section the ranging from 30 ^{o}C to 310 ^{o}C. The coolant flowed downward along the inner side and upward along the outside. The temperature in the outer chamber has a major temperature gradient at the beginning as shown in Figure 4. And the heat transfer is recognized. After about a minute, the temperature is almost stable, and the temperature adjacent to the inner chamber is higher than outer. A natural circulation is observed in the outer chamber which enhances the heat loss in the process as shown in Figure 5.

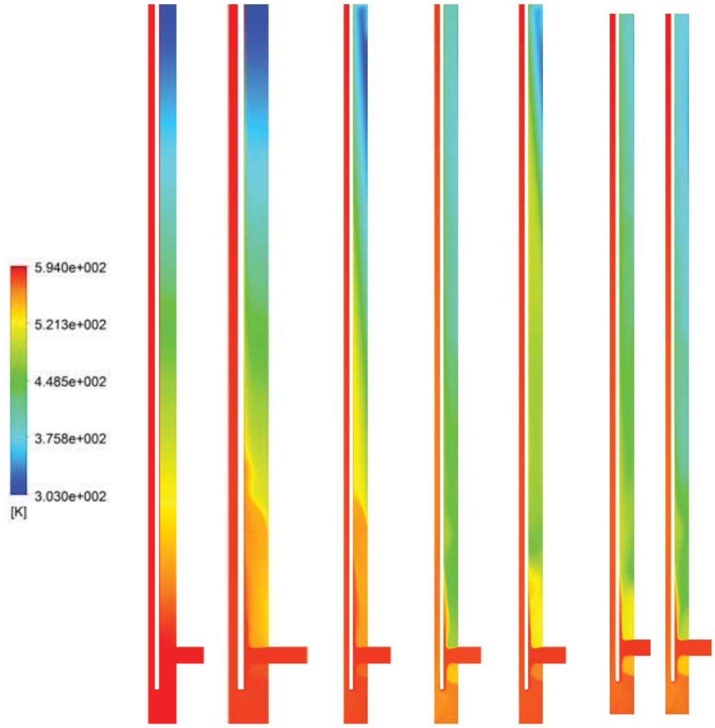

Figure 4 The temperature distribution transition from 0-60s in the test section under case 1

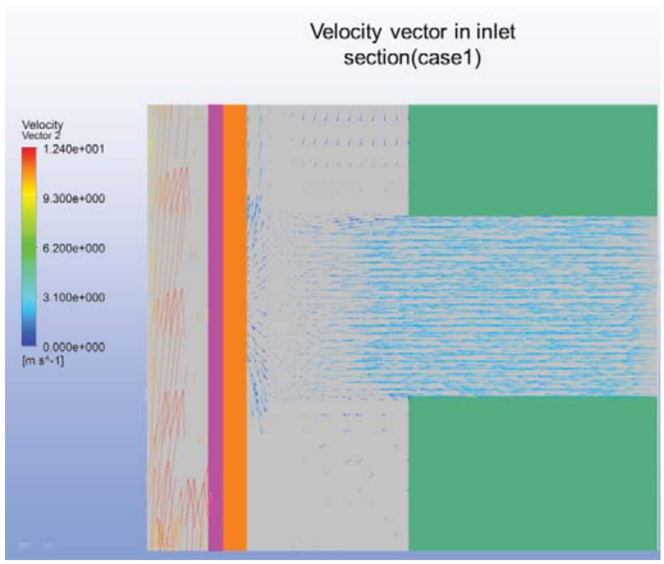

Figure 5 The flow field in the test section under case 1

b) Case 2: in this case, the outer chamber has a smaller diameter and the fluid domain is divided to total 996,658 mesh elements. Temperature distribution in the outer chamber was set as case 1. The temperature in the outer chamber has a major temperature gradient at the beginning as shown in Figure 6. After about a minute, the temperature is almost stable, and the temperature adjacent to the inner chamber is higher than outer same as case 1.

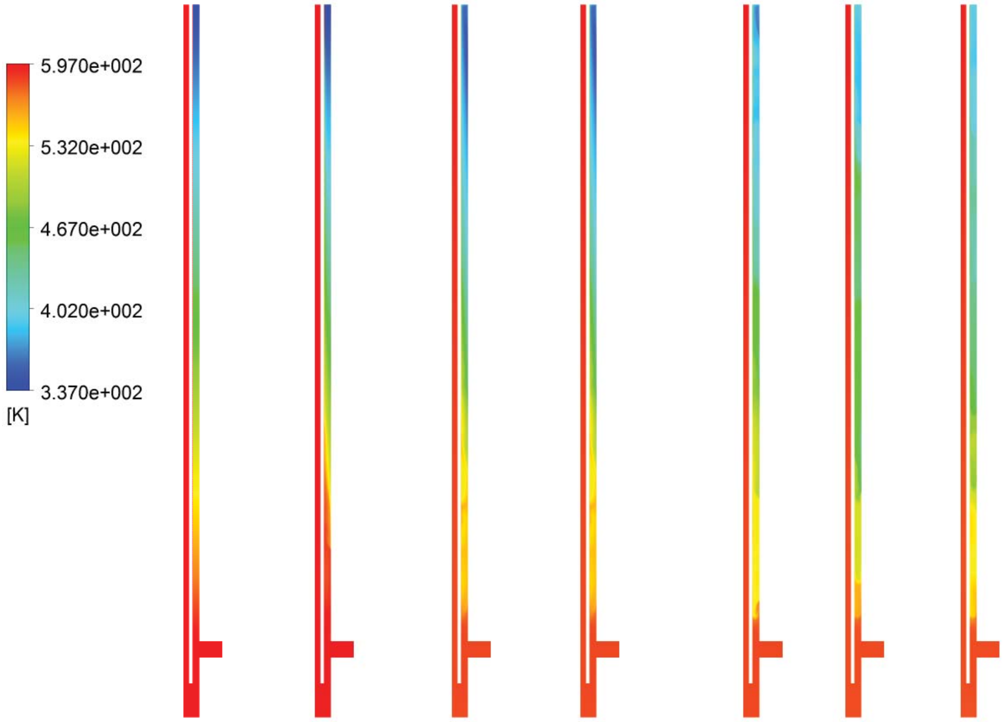

Figure 6 The temperature distribution transition from 0-60s in the test section under case 2

In the above two cases, the heat loss is varied by the time during the transit condition, and it is larger in the beginning due to the more temperature gradient in the outer chamber. After about a minute, the heat loss will decrease to a certain value, about 4-5 percent of power as shown in figure 7. In the chart, it can be found that the larger diameter chamber will induce larger heat loss due to the natural circulation in the outer chamber which will enhance the heat transfer.

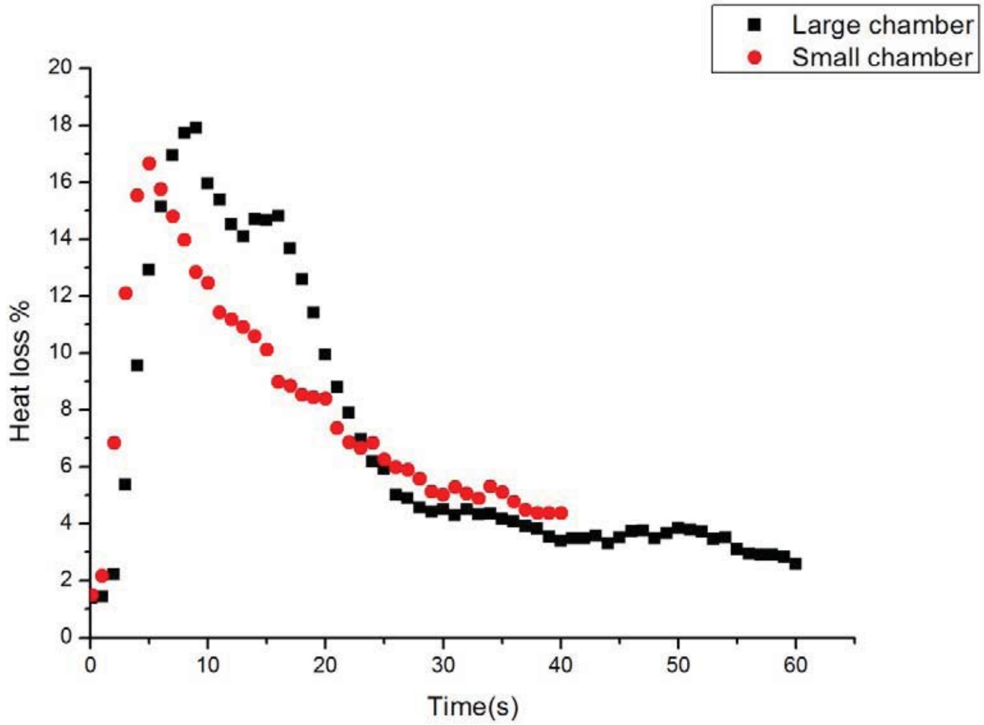

Figure 7 The heat loss in the transition conditions under case 1 and 2

c) Case 3: in this case, the outer chamber has a big diameter and the coolant inlet temperature is 120 ^{o}C. Temperature distribution in the outer chamber was set from the top of outer chamber to the near inlet section ranging from 310 ^{o}C to 120 ^{o}C which is to model the changing inlet temperature condition, and the other conditions are same as case 1. The temperature in the outer chamber has a major temperature gradient at the beginning as shown in Figure 8. After about a minute, the temperature is almost stable, and the temperature gradient is obviously due to almost no natural circulation to mix the coolant in the outer chamber under a condition that the flow temperature is higher on the top.

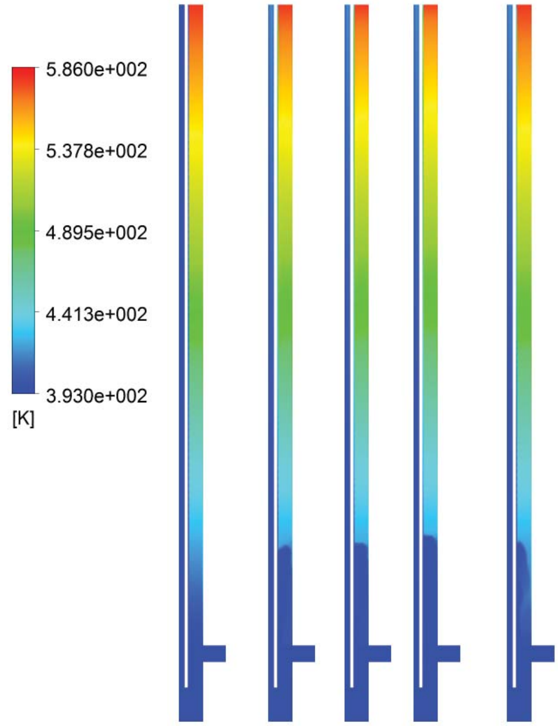

Figure 8 The temperature distribution transition from 0-60s in the test section under case 3

d) Case 4: in this case, the outer chamber has a small diameter and the coolant inlet temperature is 120 ^{o}C. Temperature distribution in the outer chamber was set as case 3 which is to model the changing inlet temperature condition, and the other conditions are same as case 2. The temperature in the outer chamber has a major temperature gradient at the beginning as shown in Figure 9. After about a minute, the temperature is almost stable, and the temperature gradient is obviously due to almost no natural circulation to mix the coolant in the outer chamber.

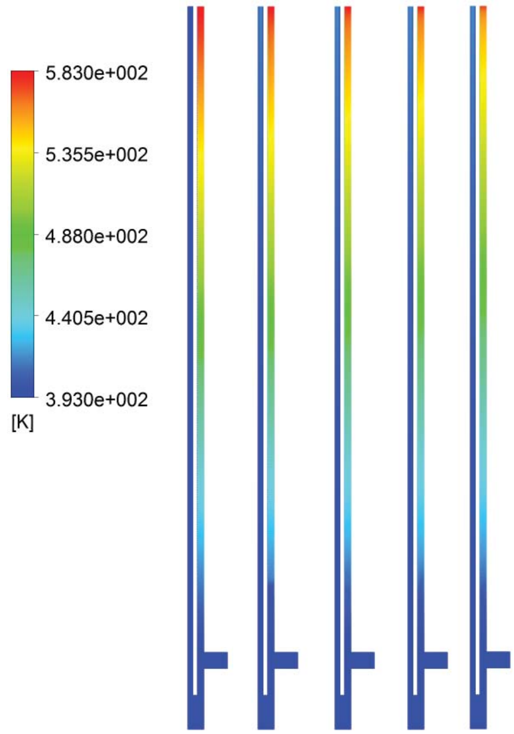

Figure 9 The temperature distribution transition from 0-60s in the test section under case 4

In the above two cases, it can be found the heat loss is varied by the time during the transit condition. Because the heat loss is defined as the heat from the inner chamber to the outer, and in these cases, the heat transfer was inversed and the value is negative. In the beginning, due to the more temperature gradient in the outer chamber the heat loss is larger. After about a minute, the heat loss will decrease to a certain value, about 4-5 percent as shown in figure 10. In the chart, it can be found the larger diameter chamber will induce larger heat loss due to larger internal energy. In the chamber , there is no condition to induce the natural circulation, the difference between the larger chamber and the small chamber is almost a constant.

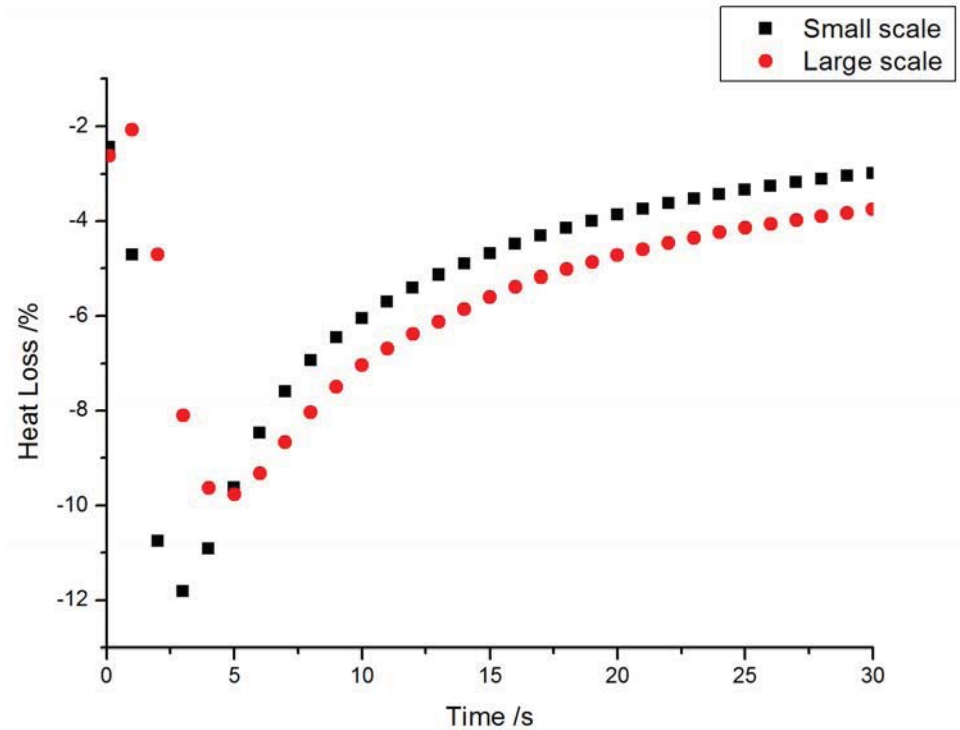

Figure 10 The heat loss in the transition conditions in the case 3 and 4

2.2.2 RELAP5 Modeling and Heat Loss Assessment

For RELAP5, the setup is divided into the nodal-junction type to model. The test section is modeled by an annulus and a pipe, which are numbered as 130 and 110. The two hydraulic models are connected by the heat structure numbered 212 which simulated the heated pipe. The flow rate is controlled by the pump 230. The node map was shown in Figure 11 and the Case 1 condition is labeled on the diagram.

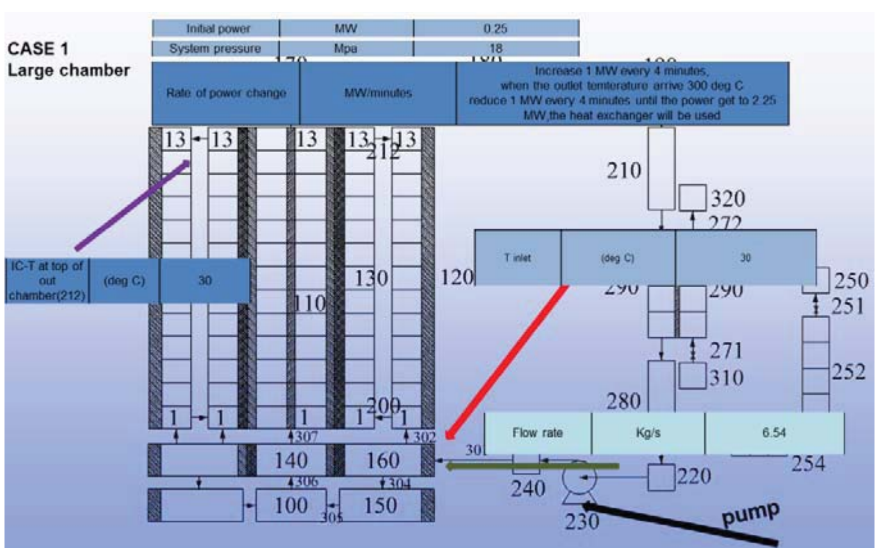

Figure 11 RELAP5 model for experimental setup

In the RELAP5 calculation, the steady state is considered, and the calculation is carried out to obtain the equilibrium condition. A range of mass flow, inlet temperature and thermal powers are adopted. For the larger outer chamber, the heat loss increased as the inlet temperature went up due to the temperature difference between the inner and outer chamber. When the inlet temperature reached about 300 ^{o}C, the heat loss will be about 5% as the CFX's results, which can verify the calculation of the CFX analysis. For different parameters varying, the trend is almost same when the inlet temperature increased as shown in Figure 12.

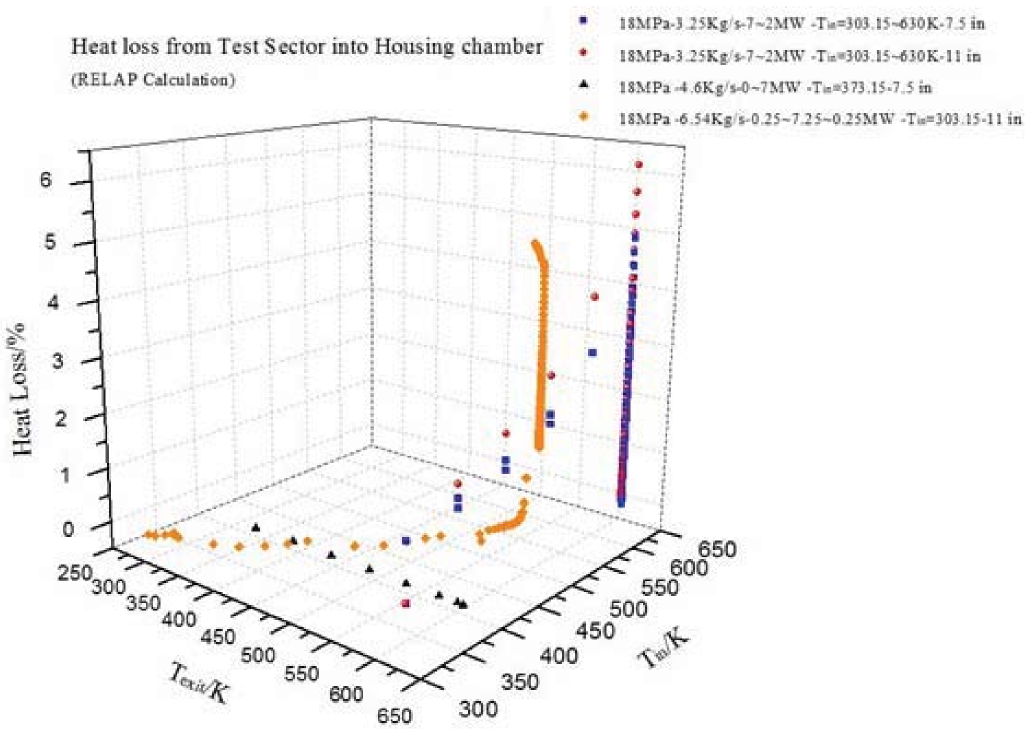

Figure 12 The heat loss obtained by RELAP5 in larger diameter outer chamber

When the RELAP is used to obtain the heat loss in a smaller diameter outer chamber, the result is same and in accordance to the CFX's result as shown in Figure 13.

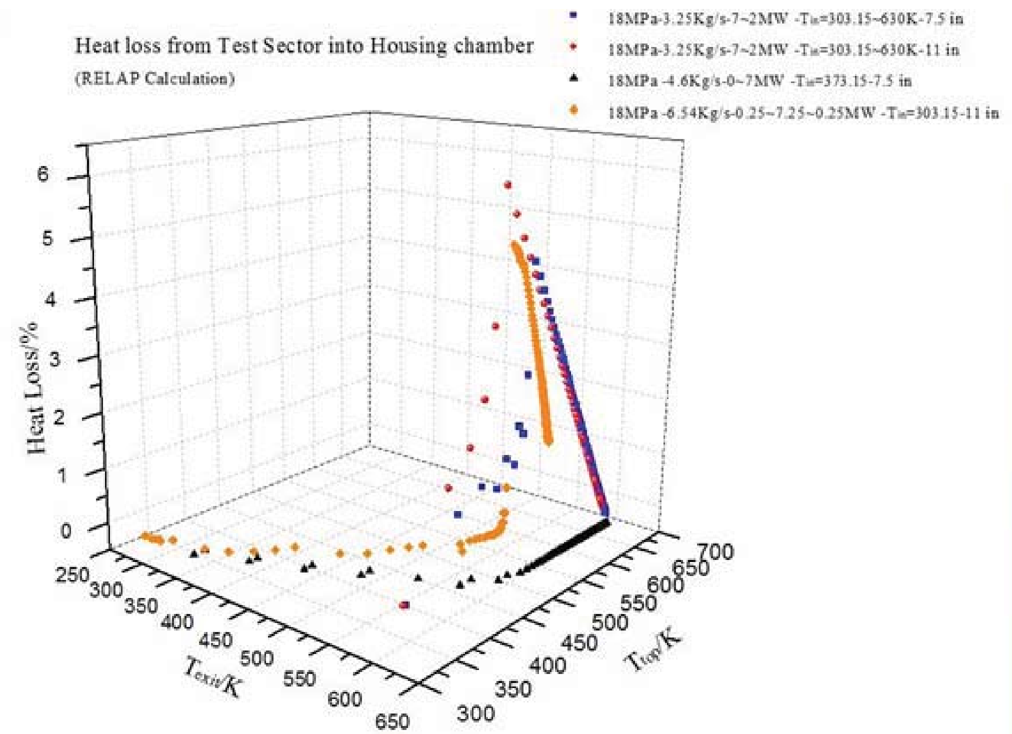

Figure 13 The heat loss obtained by RELAP5 in smaller diameter outer chamber

3. CONCLUSIONS

In the paper, the heat loss which is important to obtain the accurate results of CHF, heat transfer and other parameters used in thermal hydraulic analysis in the large scale setup is analyzed. Several main areas of heat loss exist in the test sections through outer chamber, bottom o-ring chamber, top nickel piece, bottom flanges, and others, the heat loss is difficult to measure due to the complexity phenomena. Heat Loss through Outer Chamber is investigated using RELAP and CFX modeling, and some conclusions are obtained as below.

In the few example cases, wide range of heat loss was observed (from -12% to +16% during the transient, and -4% to +5% after Steady State) depending on the operating condition. Natural Circulation plays a very important role in reaching equilibrium and heat loss which should avoid in the test.

For a large scale experiment, it is recommended that the test loop should be sufficient time to assure steady state prior to taking the CHF data point in order to minimize the impact of data quality from the uncertainty of heat loss. The test sequence also need be optimized in order to minimize the thermal hydraulic disturbance between data points in order to minimize the disturbance of the outer chamber. And the CHF tests should run in the sequence of high to low temperature to minimize the natural circulation and reduce the heat loss.

Heat loss through other components, especially the bottom o-ring chambers should be thoroughly investigated, calibrated, compensated in order to assure an accurate CHF measurement which is need further investigated.

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