Experiment of Condensation in T-junction: Steam-water Flow in Water-injected Condition

W.Y. Ren[1], G.J. Yu[1] , J.W Bian[1] ,
W.X Tian[1*], G.H Su[1], S.Z Qiu[1], X.L Fu[2,3]
[1]:School of Nuclear Science and Technology, State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, No.28,Xianning West road, Xi'an 710049, China
[2]: State Nuclear Power Software Development Center, Beijing, 102206
[3]:National Key Laboratory of Nuclear Power Software, Beijing, 10226
Tel&Fax:86-029-82663401 Email: wxtian@mail.xjtu.edu.cn

Abstract

Condensation of two-phase flow inside a tube within sub-cooled coolant injected show a complicated phenomenon which affects both the pressure drops from the upstream to downstream and the void fraction distribution in tube. This phenomenon always appears in the T-junction which kind of structure could be found in nuclear power plants design. The investigation about injection to two-phase flow in this structure can help us predict the hydrodynamic phenomenon of condensation heat transfer.

Distribution of the fluid temperature and heat transfer coefficient (HTC) due to fluid-fluid mixing and steam condensation had been considered to be a significant process which is included in the pressurized thermal shock (PTS) research. Previous researches had built the integral effect test to analysis the effect of thermal mixing. However, the practical condensate process in T-junction injected is too hard to be predict accurately, which is contributed to the structure, the geometric dimension, the mass flow rate between the main and branch pipe, the flow patterns, the void fraction of two-phase flow, temperature of flow, pressure, etc..

We analyzed the process of cooling water injecting from the branch pipe into a horizontal main pipe, and also focus on the phenomena of water injection in steam or different flow patterns. We had set some thermo couples inserting to the tube to keep observing the temperature field inside. The initial conditions of the experiment about the flow pattern before the injection includes stratified flow, wavy flow, annular flow and dispersed flow. We also took the heat dissipation between the test facility and surround into consideration. The experiment is a separate effect test program which based on the phenomena about condensation in T-junction with 45° incidence injection and progressed on ordinary pressure.

Keywords: two-phase flow, water-injected, T-junction, condensation model

1. Introduction

Nomenclature	
L_c	*aspect ratio of nozzle*
k_c	*viscosity ratio*
V	*mean velocity*
h_{fg}	*enthalpy of vaporization*
W	*mass flow rate*
C	*Constant*
A	*sectional area of pipe*
T	*Temperature*
D	*diameter of main pipe*
d	*diameter of branch pipe*
C_p	*specific heat*
μ	*dynamic viscosity*
σ	*kinematic viscosity*
h	*Enthalpy*
Π	*the ratio*
L	*structure characteristic*

During the postulated Loss of Coolant Accident (LOCA) for a Pressurized Water Reactor, the primary coolant system is calculated to void rapidly, resulting in core drying out and overheating. In the end of the blow-down phase of the accident, the safety injection pumps and the passive accumulators begin to refill and reflood the vessel step by step to cool the core from the High Pressure Safety Injection (HPSI) to Low pressure Safety Injection (LPSI). The steam generated from the core was divided into two parts which venting to the containment: One part goes through the broken loop, the other goes through the unbroken one, back to the top of the annular down-comer. At the early stages of reflooding, the steam just mixed with the accumulator water which was injected into the cold leg. As considering the direct condensation in the cold leg , the Safety Injection can condense more steam cooling to water, increasing the annular flow rate into the down-comer, which makes it available to judge the condition of the vessel reflooded. Thoroughly, direct condensation takes a great significance to the reactor safety.
The condensation on the safety injection is a rather complex phenomenon and as today not yet well understood.
P.S. Damerell et al. (1993)[1] carried out a report about the reactor safety issues resolved by the 2D/3D program**.** It studied multidimensional thermal-hydraulics in a PWR core and primary system during the end-of-blowdown and post-blowdown phases of a large- break LOCA(LBLOCA), and during selected small-break LOCA(SBLOCA) transients. It summarized the ECC's results and concluded that the loop flow regime depends strongly on the thermodynamic ratio (R_T) which is the ratio of the potential condensation rate to the steam. However the research only focuses on the R_T number and have no integral scaling analysis on heat transfer in ECC.
Jun Liao et al. (2011)[2] carried out the UPTF test, which is a large break LOCA experiment on two cold leg flow regime separate effects tests. As the UPTF tests shows, only scaling length of cold leg is modelled. The boundary conditions, such as pressure, steam flow rate, SI water flow

rate and fluid temperature are obtained from the experimental measurements. This model include both vessel and loop structure of UPTF test facility.
J.N. Ryes, Jr. (2001)[3] carried out the scaling analysis for the OSU APEX-CE integral system test. As it has an integral system, the test use H2TS solution with Top-down and Bottom-up analysis. As the thermal fluid mixing, the analysis included HPSI flow rate analysis, Bottom-up scaling analysis for the onset of backflow at the HPSI nozzle, the onset of cold leg thermal stratification (hydraulic jump leading to perfect mixing) and HPSI plume entrainment and temperature decay. The scaling analysis is quite suitable to the integral system test but may not focus on the separate effects tests.

In former study, the research always focus on the steam phase safety injection. However, the recent research offers that it's possible the two-phase flow can grow in the cold leg ECC on SBLOCA accident. Also, most research construct an integral system test experiment for discussing the whole coolant loop, less of them take scaling analysis on the separate effects tests just as direct condensation heat transfer in ECC.

2. Experiment Analysis

2.1 Experimental System

The ECCS (Emergency Core Cooling System facility) experiment war performed by Xi'an Jiao tong University, The ECCS test loop is modeled after CPR1000 (which was a type of Chinese PWR) with a diameter scaling ratio of 1:10 both the cold leg and safety injection parts, the diameter of main pipe was 70mm and 20mm for the branch one. In order to make the cold water fill full in branch pipe, the size of branch was a little bit smaller than the scaling down by PWR's ECC line. The pressure of experiment operated in atmospheric pressure. The range of scaled flow rates between the cold leg and branch expected a PWR LOCA steady condition: During SB LOCA, as the ECCS launched, the break running over 100 second cause the pressure falling to low level. Pressure drop lead the coolant which circulated in the cold leg change phase to steam, the condensation on the safety injection water is an identified important phenomenon. The main scaling philosophy followed in designing system was to maintain similar fluid stats (temperature and pressure) and ensure the similar flow regime in the cold leg, and the regime by the test considered to stratified flow. We got 90 seconds of samples during every steady state test point.

The ECCS test loop was designed in detail, including mechanical part, data acquisition and measurement system, power regulating system. Two plunger pump with high head of delivery, heater's power about 220kW, condenser, reheater and boiler. The schematic of the test facility is shown in Fig.1. ECCS lab was constructed in November, 2013 and completed in March, 2014. The boundary conditions of the test facility can be easily transformed to satisfy various experimental conditions. The test loop can offer varieties of two phase flow experiment. Over 50 transducers are used to measure various parameters, actually most focus on the temperature field of ECCS. The condition of the experiment is shown in table 1. The upstream steam and water mixed to different flow pattern.

Table 1 Test boundary conditions of ECCS loop

Condition	Sub phase	
Main Pipe flow pattern	Steam	Two phase flow

<table>
<tr><td>Pressure(MPa)</td><td colspan="12">0.10</td></tr>
<tr><td>Saturation Temperature(℃)</td><td colspan="12">100</td></tr>
<tr><td>Upstream Steam Flow(kg/h)</td><td>25</td><td colspan="2">50</td><td colspan="3">75</td><td colspan="3">100</td><td colspan="3">125</td></tr>
<tr><td>Upstream Water Flow(kg/h)</td><td colspan="5">/</td><td>100</td><td colspan="2">200</td><td>300</td><td colspan="2">400</td><td>500</td></tr>
<tr><td>Upstream Water Temperture</td><td colspan="5">/</td><td colspan="7">93~97</td></tr>
<tr><td>Steam Temperature(℃)</td><td colspan="12">102~103</td></tr>
<tr><td>ECC Flow（kg/h）</td><td colspan="2">100</td><td colspan="2">200</td><td colspan="3">300</td><td colspan="3">400</td><td colspan="2">500</td></tr>
<tr><td>ECC Temperature(℃)</td><td colspan="12">30</td></tr>
</table>

A removable weir was incorporated in the outlet of the cold leg to changing the fluid level retained within the cold leg pipe. Measurements were available for steam and liquid flow rates between inlet and outlet assembly, for the temperature of fluid entrance and exiting, and also for controller's local pressure and the differential pressure both the main pipe and branch pipe from upstream to downstream. For acknowledge the mass void after mixing, the experiment supported a gamma-ray measuring to research which preserved caesium inside. All test-loop were covered by the thermal insulation material to keep heat preservation.

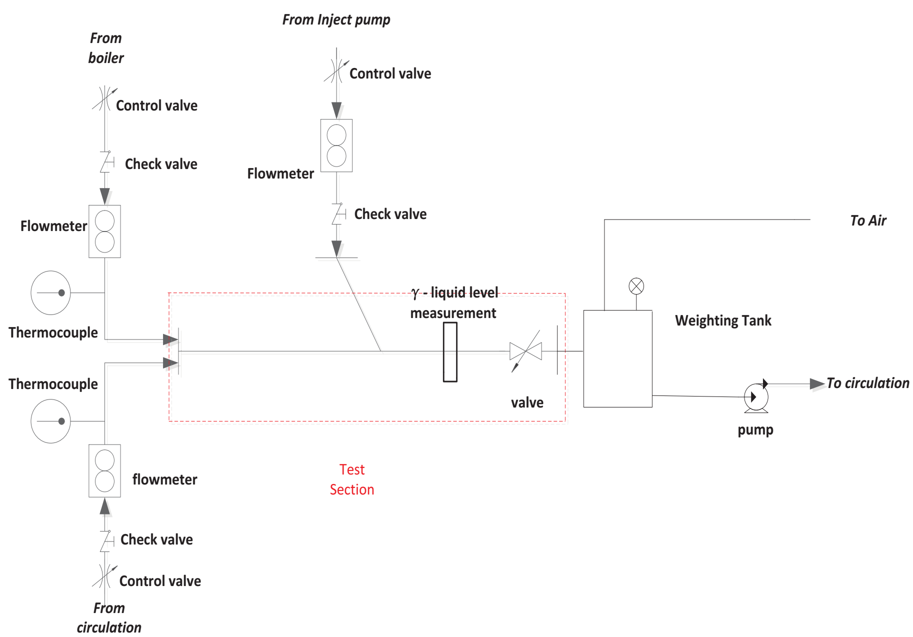


Figure 1. ECCS Facility

More detail pictures of the T-junction test section is shown in Fig.2. The injection part was contacted to the cold leg pipe with a 45 degree tees. A length of visual window which was made by polyvinyl chloride(item 7 in Fig.2) offered an opportunity to observe the flow regime in the upstream before the safety injection. There was few of temperature measurement cross-section arranged in the cold leg. As the cross-section was considered to understand temperature distribution of the fluid inside the cold leg, as considered to be a unique structure which shown in Fig.3. One cross-section got six K-type thermocouple that through the wall of pipe and plug in different location.

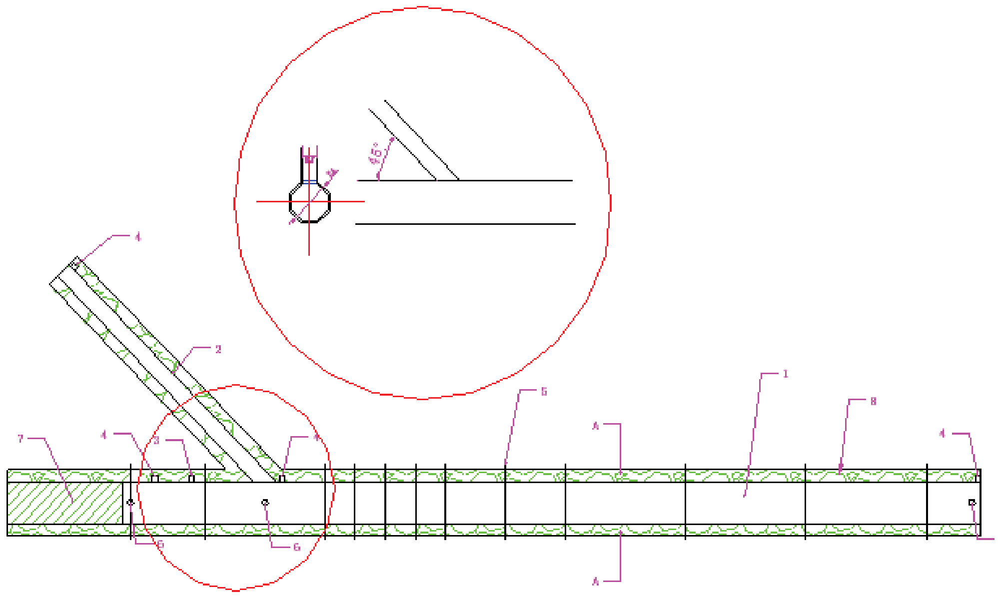


Figure 2. Structure of T-junction test section

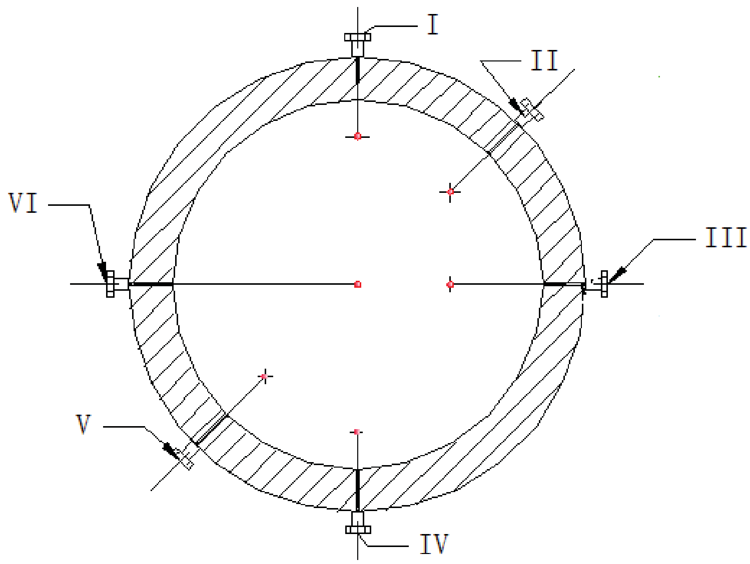


Figure 3. Cross-section with thermocouple

2.2 Condensation Modelling Analysis

The experimental modelling followed Janicot.A and Bestion.D[4] which research the direct contact condensation for thermal hydraulic codes as CATHARE (Code for Analysis of Thermal

Hydraulics during an Accident and for Reactor safety Evolution). Its COSI experimental program was developed to simulate and study ECC injection.

The COSI controller which was analysed the condensation about the T-junction injection separated to three zone: Recirculation zone, high turbulent mixing zone and stratified flow zone. The structure was shown in Fig.4.

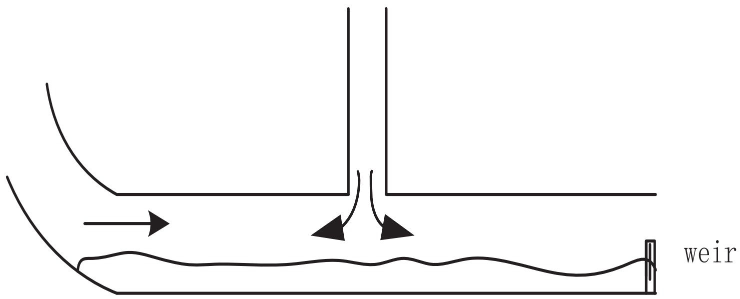


Figure 4. Schematics of flow regime and condensation in COSI experiment.

A simple energy balance based on the liquid experimental temperature at the injection has been used to estimate the additional heat flux induced by the jet. The additional heat flux at the interface is expressed as followed:

$$Q = Ah\Delta T \tag{1}$$

The *"h"* is the interfacial heat transfer coefficient and ΔT is the temperature difference between the steam and the safety injection water, where A is the interfacial heat transfer area which is hard to be determined. As defined that the heat transfer area should relate to the geometry construction between the cold leg and the branch one, which goes to:

$$A \propto Ld \tag{2}$$

Where d is the diameter of safety injection line.

The condensation heat transfer coefficient is non-dimensionalized by the following Nusselt number:

$$Nu = \frac{hL}{k} \tag{3}$$

Where k is the heat conductivity of the safety injection water, L is the characteristic length determined by cold leg diameter and liquid volume fraction.

Introducing upside equation, the Nusselt number simply writes to:

$$Nu = \frac{Q_{cond}}{dk\Delta T} \tag{4}$$

Such Reynolds number is defined using the safety injection water velocity, density viscosity and the pipe diameter, which as follows:

$$Re_{SI} = \frac{\rho Vd}{\mu} = \frac{4M_{SI}}{\pi\mu d} \tag{5}$$

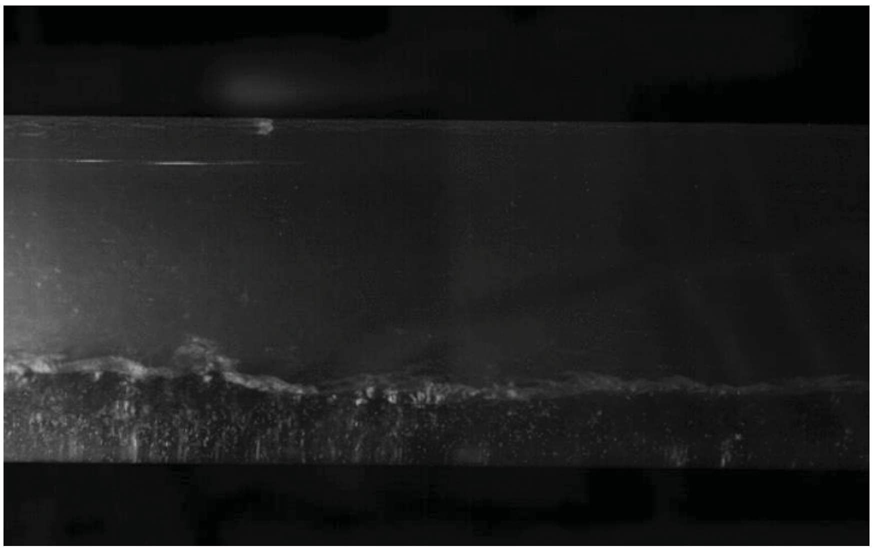
Next, a correlation between the Nusselt number and Reynold number is built up to similar the traditional Dittus-Bolter forced convection heat transfer correlation:

$$Nu = CRe_{SI}^{m} Pr^{n} \tag{6}$$

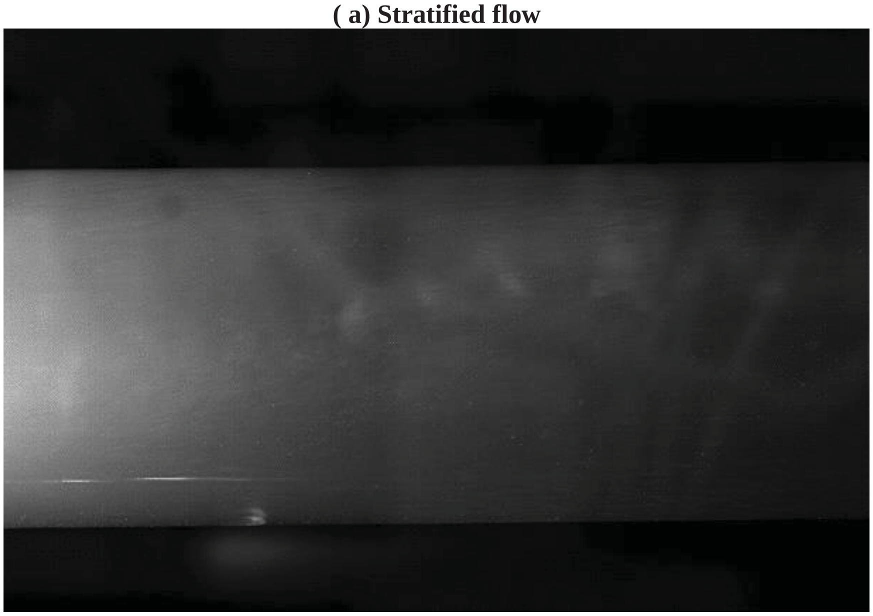
3. Experimental Correlation

Condensation in T-junction as considered depends on the pressure, structure, mass flux, void fraction, coolant's sub-cooled temperature and the mass ratio of flow rate between the cold leg and the safety injection. Different between the former research, XJTU-ECCS test raise the upstream flow regime to be an important role to analysis different condensation between different flow regime, such as stratified flow, bubbly flow and annular/mist flow.

To compare with the former research, the author order to test the condensation in the stratified flow, annular flow and mist flow condition. The example of video captured picture was shown in Fig.5.



(a) Stratified flow



(b)Mist Flow

Figure 5. Typical flow regime before condensation

In this condition, the flow in cold leg pipe was contained with the saturation steam and saturation water which was similar with the realize flow regime when SBLOCA happened. The test used various group of ratio between the steam and water to research the effect of the mass void gas.

As it's considered that all the screen out test condition were stays in stratified flow. The test should be ensured that flow pattern keep in steady state.

In this development, the safety injection pipe started to send out the subcoolant. The evidence form the experimental data shows that the sub-cooled water can cool down the temperature of the fluid in the cold leg. Checked that all system were in steady state, the weighting tank started to record. Then compare with the total mass flux of cold leg add safety injection pipe and the mass increasing from the weighting tank, the correlation of condensation presented.
To estimate the mean temperature of the liquid flow which had sufficient thermal mixing by the cold leg coolant, the experiment used gamma-ray measuring instrument to measure the liquid level. Assumed that the temperature measured by the thermocouple IV(Fig.3) was approximate to the temperature in the bottom of the tube. The temperature of the interface between the liquid and steam are saturated. Supposed the temperature was linear growth from the bottom to interface. Then the mean temperature of the liquid flow could be solved by definite integration. The cross section of cold leg was shown in Fig.6

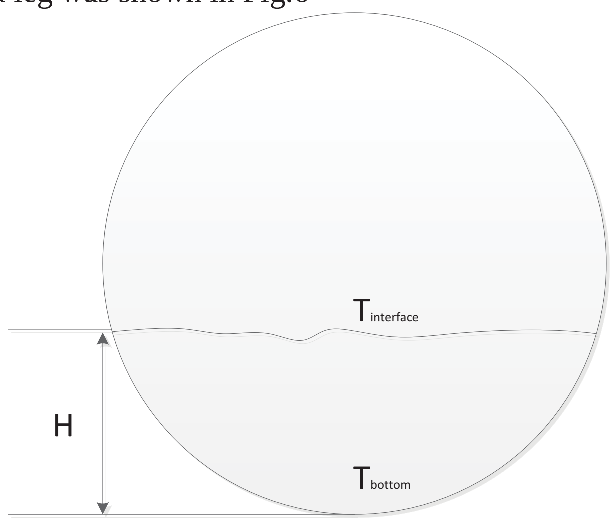


Figure 6. Cross section of cold leg near after condensation

Fig.7 show the correlation on the steam water-injected of ECCS experiment data. At this point the dependency on the *Pr* number is neglected. The result is the relation between the *Re* and *Nu.*

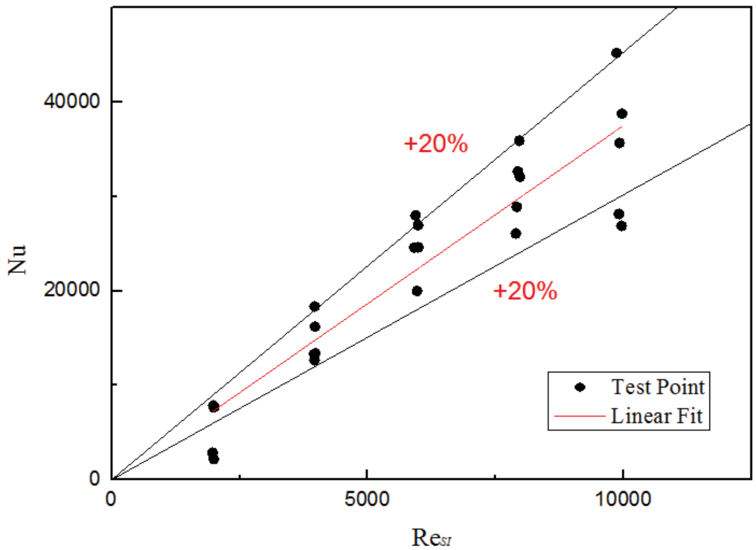


Figure 7. Experimental relationship between Nusselt number and safety injected Re number: steam flow in water-injected

The following correlation was obtained using best fit to the ECCS data.

$$Nu=3.773Re_{SI} \tag{7}$$

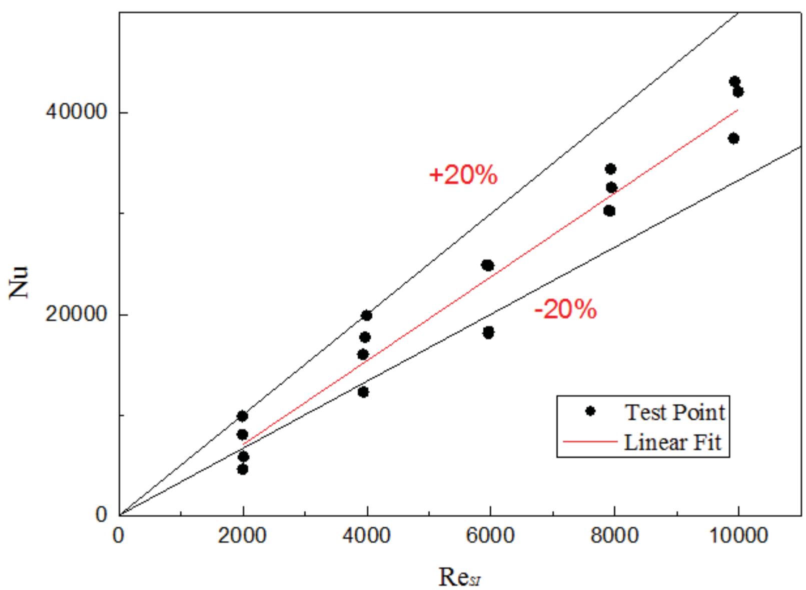


Figure 8. Experimental relationship between Nusselt number and safety injected Re number: mist flow in water-injected

Fig.8 show the correlation on the mist flow water-injected of ECCS experiment data. The following correlation was obtained using best fit to the ECCS data.

$$Nu=4.170Re_{SI} \tag{8}$$

4. Discussions

4.1 Limitation of Condensation with High R_T number

Paul H. Rothe, Graham B. Wallis, David E. Thrall[5] put forward a thermodynamic ratio which support the possible energy transfer rate by the water to that of the steam during mixing to equilibrium conditions. The original character of thermodynamic ratio goes to:

$$R_T = \frac{W_j C_p \Delta T_{sub}}{W_{stm} h_{fg}} \tag{9}$$

The molecular part of the equation indicate the character of ECC injection's latent ability to condense steam form the main pipe. The denominator part of the equation indicate the energy that all the steam cooling to liquid phase needed. At R_T=1, it is possible to just condense all the steam while raising the water to saturation temperature. As R_T＜1， the sub-cooled water didn't have ability to condense all the steam.

Chosen one group of ECCS test (50kg/h steam in water-injected) and tried to get the repetitive test, it have been found that when R_T number stay in a very high level, which means the sub-cooled water was enough to condensate most steam in the main pipe, the mass of condensation should not increase with more cold water injected. The relation between the mass of condensation and the mass flux of steam was shown in Fig.9.

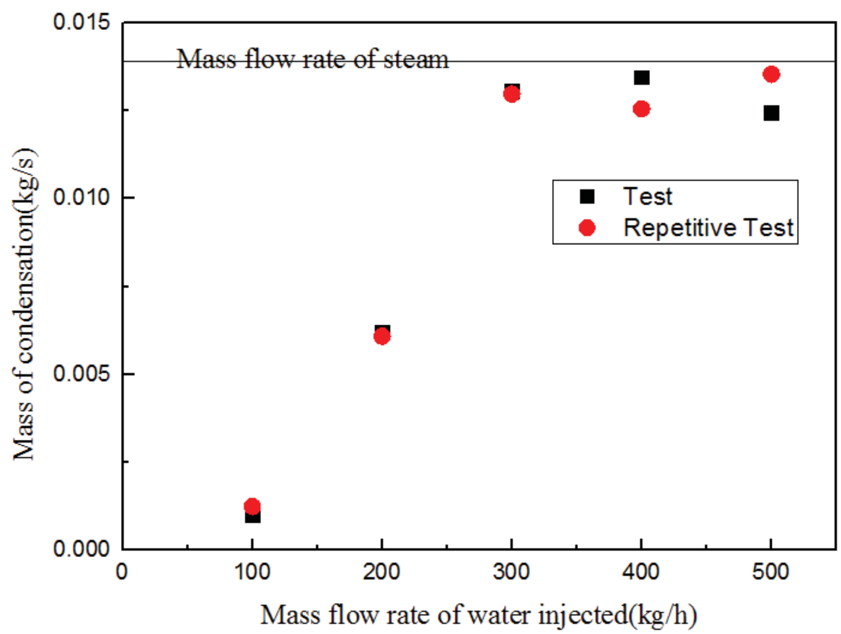


Figure 9. Mass flow rate of water injected effected on condensation

The data from ECCS's test illustrated that it might have a limitation of the mass of condensation.

4.2 Analysis the Effect on the Inlet Flow Regime

As it illustrated in Fig.8, there is two structure between the COSI test and ECCS test. The COSI test[6] got the correlation which was obtained using fit to the data, as following:

$$Nu=1.7Re_{SI}^{1.1} \tag{10}$$

The ECCS test correlation have more coefficient between the *Nu* and Re_{SI}, which means the ECCS's structure got more condensation efficiency on the T-junction.

Compare the COSI's structure (Fig.10), the angle of the injection was 90 degree however the ECCS one was 45 degree. The result showed that the incline of branch pipe could induce more heat transfer on the area of T-junction, which inevitable could condensate more steam from the cold leg. The effect of the back-flow on the COSI test probably block the directly contact condensation on the area of T-junction. As the result of ECCS test, the incline of branch pipe could increase the area of heat transfer between the interface of the subcool water and the steam.

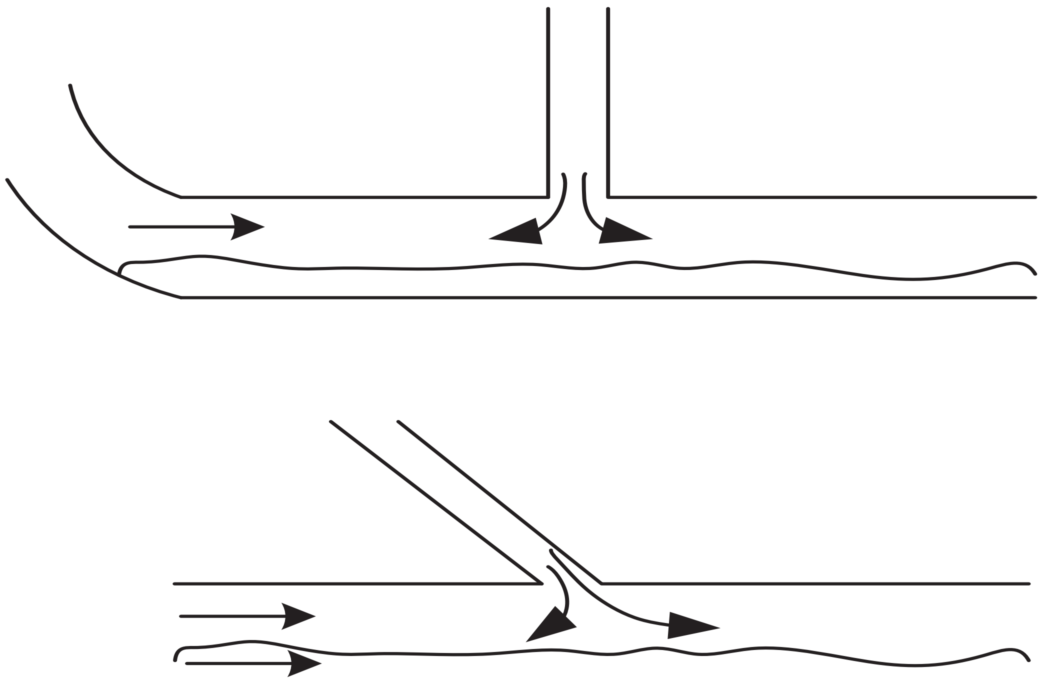


Figure 10. The controller of COSI and ECCS

The other important factor which effected the condensation in T-junction is the slip ratio of the two phase flow in cold leg. For the COSI test, the water in the cold leg stayed in a low rate because there was set a block in the end of the cold leg. The flow level was contributed to the injected sub-cooled water. So the slip ratio of the two phase flow in cold leg on COSI test always keep in a high level, whatever from the upstream to downstream. Too low flow rate of the water phase should reduce the area of the heat transfer on interface. In ECCS test, the initial condition of the flow regime on the upstream varied three kind: stratified flow, annular flow and mist flow. The saturation steam and water mixed, and changed to different pattern before the branch cold water injected. Especially the fluxion of the water phase could bring more heat convection with the sub-cooled injected water.

5. Conclusion

Comparing the correlations between ECCS and COSI, the test of steam flow in sub-cooled water-injected illustrated that:

1) The incline branch offered more directly contact condensation and more heat transfer when sub-cooled water injected;
2) The correlation of steam in water-injected which best fit to the ECCS data goes to: $Nu=3.773Re_{SI}$
3) The mass of condensation should have a limitation that was less than the mass of upstream-steam. The result is just under the law of mass conservation.

The result of mist flow in water-injected illustrated that:

1) With the same steam flow rate and similar R_T number in different mass flow ratio, the mass of direct contact condensation always appears similar. It means that the steam inside two phase flow was play an important role decided the result of condensation in T-junction.
2) The flow regime before sub-cooled water-injected effect a little on the condensation in T-junction. Matching the correlation between the only steam and the mist flow, the coefficient between the Nu and Re_{SI} are approximate.

6. References

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