博士論文（要約）

A study on the effect of surface oxidation on critical heat flux in downward-face boiling

(表面酸化による下向き沸騰の限界熱流束に関する研究)

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An increasing amount of focus has been placed on nuclear safety since the Fukushima accident. External reaction vessel cooling (ERVC) is regarded as an effective method commonly used in many Generation III reactors in order to contain melted core materials within a RPV after an accident. However, this type of strategy is limited by the maximum heat flux in the nucleate boiling regime according to the boiling curve. Nucleate boiling is the most meaningful part of the boiling curve because of its high heat transfer coefficient. In this regime, large numbers of bubbles are generated and removed from the heating surface, which can act as an effective method for removing the heat. Therefore, the superheat and bubble behavior are important elements in research on nucleate boiling. However, when the critical heat flux (CHF) exceeds a certain upper limit, the boiling process will change from nucleate boiling to film boiling (or transit boiling) and the superheat will be extremely high. This will cause the heat transfer coefficient to significantly decrease, which will result in a heating surface burnout. In this sense, it is very important to investigate the CHF phenomenon. In real-world applications, the RPV outer surface is exposed and oxidized. So it is very important to study the oxidation effects on boiling and CHF. In this study, we performed experiments as well as numerical simulations to study the oxidation effect.

For the experiments, several experiments were done.

Downward-face flow boiling CHF enhancement by copper oxidation in the air was investigated under atmospheric conditions. The copper surface was polished and then put into a drying oven for 1 h, 3 h and 6 h under 300°C. The main conclusions are:

After oxidation, copper CHF increased and fewer bubbles were found to generate on the surface.

The copper oxidation flow boiling experiment was done in three different massflow rate and CHF enhancement was found at each massflow rate, but the CHF enhancement ratio decreased in higher massflow rate.

It was found that the NSD and CHF had a reversed relationship.

The surface of the non-oxidized and oxidized copper was observed by SEM and some cavities were filled with the oxidized particles, which is why NSD decreased after oxidation.

The CHF enhancement is related to the decrease in contact angle and NSD.

Due to the easy oxidation on copper and the big influence surface modification has on CHF, it is imperial to check the surface condition when doing flow boiling experiment. However, there is an upper limit on the oxidation effect, so it is recommended that a certain time of oxidation on the surface will give a rather stable result. The results implied that the oxidation process could be a convenient, easy and cost-effective way to improve CHF of the heating surface while at the same time, it may cause a deterioration in heat transfer.

Then an experiment concerned with the downward boiling CHF using a carbon steel block was performed and the results were analyzed through a comparison with the CHF of a copper block, and the block is positioned on slope that is declined at angles of 5° and 10°. The conclusions are as follows:

The carbon steel block CHF under both 5° and 10° inclination angles were much lower than that of the copper block.

As seen from the surface images, the carbon steel block generates more bubbles than the copper block, which leads to more dry patches. This may result in lower CHF.

Using the inclination angle and contact angle only may not be sufficient to explain the large difference between the CHF of the carbon steel and copper blocks. However, using the thermal effusivity effect might explain the big difference between the two materials since their thermal effusivity also differs a lot.

Even though no quantitative results were obtained, we believe this study makes a breakthrough in understanding the mechanism of CHF differences between different materials. In addition, we found that copper and carbon steel behave differently under the same test conditions, which means that additional studies on carbon steel are needed if we want to utilize it in real-world applications.

To elucidate the CHF difference between copper and carbon steel more definitively, additional work is needed, including a thorough study of additional angles, and a detailed inspection of the material surface (nucleation sites and so on).

At last, a downward-face pool and flow boiling experiment conducted using a carbon steel plate and compared the results with those of previous experiments is introduced.

The conclusions for the pool boiling can be summarized as follows:

During boiling, as the boiling time increases, the CHF increases gradually and fewer bubbles are generated on the heating surface.

Under different heat fluxes and surface conditions, the BFDF remains almost the same with a downward inclination angle of 10°.

The CHF increase is due to iron oxidation on the heater surface. The combined effect of the increase in wettability and decrease in NSD is likely to be the reason that the CHF increases.

The conclusions for the flow boiling can be summarized as follows:

During the boiling process, CHF increased gradually as fewer bubbles were generated on the heating surface.

CHF increased with boiling time at each massflow rate; however, the CHF enhancement ratio decreased with increasing massflow rate. This is because at low massflow rates, generation of fewer bubbles had a significant impact on improving CHF as bubble removal ability was weak. At high massflow rates, generation of fewer bubbles did not have a significant influence on CHF because the bubble removing ability was strong.

A correlation with boiling time based on the Katto's correlation agreed well with the experimental results.

The liquid-vapor mixture area decreased with increasing heat flux in one of the experiments. Furthermore, with increasing boiling time, the mixture area decreased under a constant heat flux, which delayed CHF.

Increasing CHF contributed to increasing the wettability and decreasing the NSD.

This experiememts provides unique insight into the mechanism of the CHF increase observed upon oxidation, which occurs in many industrial applications. This phenomenon can be considered an advantage for the ERVC process because, in actual situations, the surface may endure several repeated CHF occurrences. However, additional work is necessary, including a thorough study of more angles, detailed inspection of the material surface (nucleation sites, roughness, and so on), and investigation of whether there is a threshold for this kind of oxidation.

From the results of the experiments, it was believed that CHF enhancement was related to the decrease of NSD. Based on this observations, a new model for the downward-face pool boiling and flow boiling CHF based on the bubble interaction theory was proposed. The relationship between NSD and CHF was revealed as $q_{CHF} \propto N_{density}^{-\frac{1}{2}}$, several experiments and numerical simulation were applied to validate the model. The relationship between CHF and NSD agreed well with the experimental data for both the flow boiling and pool boiling. The MC method was applied to simulate the bubble behaviour on the surface. Bubbles were generated on the surface by a general rule. It showed that with fewer NSD, fewer bubbles generated and the averaged isolated bubble rate also increased with decrease of NSD, which showed that more water may be supplied to the surface and thus delay the CHF.

A numerical simulation study was done to simulate the ultra-high CHF phenomena of vertical tubes and compared with the benchmark experiment to ascertain the effects of tube diameter, heated length, massflow rate, subcooling and pressure on CHF. And also the effect of NSD was also investigated. The conclusions are:

Eulerian two-fluid model coupled with extended RPI wall boiling model can be used in the simulation of ultra-high CHF phenomena.

Koca-Ishii NSD model, Koca bubble departure model and Koca-Ishii bubble departure frequency model can give better results in the simulation of subcooled boiling.

Simulation results shows that ultra-high CHF increases with increasing massflow rate, increasing subcooling, increasing pressure. And the predication has the same trend and agree with the experiment.

CHF increases decreasing heated length and decreasing tube diameter. The longer heated length will initiate earlier ONB and thus leading to earlier CHF, and different tube diameter case have the same ONB, but different CHF.

Bigger NSD will have more bubbles and thus enhancing the heat transfer coefficient, but smaller CHF.