Study on Basic Analysis Method of Critical Heat Flux in Energy System

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Abstract. The parameters of molten salt heat storage power generation system are continuously improved. The boiling crisis caused by deterioration of heat transfer in such system is studied and the basic mechanism and influencing factors are explored. In traditional theory the dry area of the bubbles are the cause of sudden overburning. In this paper the physical phenomenon is simulated by a variable heat convection boundary condition. Based on Fluent, four factors, including growth rate of dry area, size of dry area, size of pipe and shape of pipe, are simulated and analysed numerically to figure out what effect they have on wall temperature rise. The calculation results show that if final size of dry area is consistent, the dry area’s expansion rate will have little influence on wall temperature because time for temperature to rise is much more than that for dry area to grow; The highest temperature rise is directly dependent on the size of dry area, and is also affected by the size of pipe, which is related to volume heat flux; Corner of square pipe is more likely to face the boiling crisis than centre region. In order to burn the pipe wall, there must be a large area of heat transfer deterioration lasting for quite a long time, so the most cases of the wall damage is due to thermal stress instead of traditional statement “burning”. This method provides a new analytical perspective and has guiding significance for experiment and theoretical analysis in the next research plan.

Keywords: critical heat flux; dry spot; numerical simulation

Introduction

With the development and utilization of energy technology, there have been a large number of theoretical and experimental research on Critical Heat Flux (CHF) which have to be avoided to reduce the damages of devices in energy system. Now in molten salt heat storage power generation system the operation parameters become higher and higher, such as in the Chinese Academy of Sciences some researchers suggest the temperature of molten salt will be over 750 degrees centigrade. At the same time the molten salt heat storage power generation system have frequent charging and discharging process. During the heat exchange process, especially in the transient operation condition, the heat transfer deterioration area maybe occur in the pipe system, and the temperature of pipe will rise very quickly. The mechanism of CHF is very complicated in traditional views. There are roughly four explanations for it: The first is Liquid Sublayer Dryout[1-2], which is suitable for the undersaturated flow boiling with the mainstream of low subcooling degree; The second is Near-Wall Bubble Crowding [3-4], which is suitable for saturated flow boiling with low dryness. The third is Liquid Film Dryout [5-6], which is suitable for saturated flow boiling with high dryness. The fourth is Interfacial Lift-off proposed by Galloway [7-8], which is suitable for under-saturated flow boiling with the mainstream of high sub cooling degree. In general, most scholars believe that heat transfer deteriorates in the local near-wall area, resulting in sharp rise of wall temperature and eventually wall overburning. All the explanations mentioned above need heat transfer deterioration. So traditional
analysis methods for this phenomenon focus on describing the cause and process of heat transfer deterioration. However the reason is caused by two phase flow, such as bubble, micro liquid layer, liquid film dryout and so on, all of them are very complex. It seems the CHF problem cannot be solved accurately until the two phase flow and turbulence are clearly understood. In present paper the traditional theory is challenged. The process of wall temperature rising and its influencing factors will be simulated and analysed numerically by assuming extreme deterioration of heat transfer boundary conditions. The wall may be damaged by thermal stress cause by temperature rising constantly instead of overburning. Moreover, the temperature of pipe wall is not rising as fast as conventional theory suggests.

**Analysis**

Figure 1 shows the calculation domain, which is the solid domain of the round steel pipe whose length is 50 mm. The outer wall is the heating surface, whose surface heat flux is given to ensure that surface heat flux of the inner wall is 1 MW/ m². The heat transfer coefficient of the inner wall surface is related to time and space to simulate the spread of dry area. It is assumed as 10000 W/ (m²*K) in the initial moment to simulate the heat transfer with liquid, such as water. Then a very small region (figure 2) such as several grids are assumed as 10 W/ (m²*K) to simulate the heat transfer deterioration region, such as dry area. The walls on the ends of pipe are adiabatic. The number of mesh in figure 2 is 15120.

![Figure 1. round pipe](image)

Four factors will be considered, including growth rate of dry area, size of dry area, size of pipe and shape of pipe. All the parameters set here are much severer than those in traditional theories and experiments, such as the stretch rate and area of heat transfer deterioration. For example, according to the theory of Near-Wall bubble crowding, heat transfer deterioration region is formed by the continuous accumulation of bubbles. Assuming that the final size of dry area is 10mm long and 10mm wide, four rates are used to analysis the effect of growth rate of dry area. As is shown in figure 3, A is
the bubble growth rate, B is a linear growth rate, C is twice the rate of A and D is half of A. The growth rate and curve of bubble are referred to reference 9 and 10. Besides, the highest temperature rise is undoubtedly in the centre of the dry area, so it’s directly dependent on the size of the dry area. Three situations will be considered and analysed, including a square dry area, a rectangular dry area, and the dry area in a thin pipe. In addition, effect of pipe size will be studied by changing the inner and outer diameters. Furthermore, square pipe will be compared with round pipe to analysis how shape of pipe affects the temperature rise.

![Figure 3. three expansion rates of dry area](image)

**Results and Discussion**

1.1. Growth rate of dry area

Figure 4 shows the maximum temperature rise curves with time for four expansion rates of dry area, which are simulated in a tube whose outer diameter is 22mm and the tube thickness is 3mm. For case A and case B it just takes 0.29 seconds for dry area to grow up. And the time for cases C and D are 0.1 seconds and 0.9 seconds. However, all the cases cost more than 10 seconds for the wall temperature to reach the maximum value and new stable state. And the curves are almost same. Therefore, the growth rate only slightly influences the temperature rise process. Although the dry area forming speed changes much the maximum temperature and forming procedure are very similar. The reason can be found in the basic theory of heat conduction. The heat flux redistribution time is longer than the dry area forming time. Once the dry area is built the following procedure tends to be consistent. After that the temperature rise curve only depends on the heat flux redistribution process until new stable state is built. So the temperature rise rate is mainly influenced by which stage it is at, it can be up to 108K/s in the initial moment and quickly reduce to 11K/s in the middle of heat flux redistribution process, and eventually there is nearly no temperature rise in the later stage. Besides, the final temperature is the same if the dry area is consistent.
Figure 4. Temperature rise curves for four growth rates

1.2. Size of dry area
If the size of the tube is large enough the dry area will grows in all directions. A square zone whose length and width are both increasing synchronously is used to simulate this situation. In figure 5 it can be found that the temperature rise increases with the increases in length and width. It must be mentioned that all the data points are taken from the centre and all the new steady states are established after about 10 seconds.

Figure 5. Relationship between highest temperature rise and dry area
In figure 6, the length of dry area (pipe axial direction) is fixed as 10mm and the width (pipe circumferential direction) increases from 1mm to 19mm. The temperature will increase slowly when the width is more than 10mm. It is obvious that heat power is more likely to be conducted away from the shorter side.
Figure 6. Relationship between highest temperature rise and the width of dry area

1.3. Thickness of pipe
The same dry area whose length and width are both 10mm is placed in different pipes to test the influence degree. The inner diameter of all pipes is kept as 10mm to make sure that the dry area makes up the same proportion in inner surface. Volume heat flux is changed by changing the thickness. The heat flux of inner surface is kept as 1MW/m². As seen in figure 7, the impact of thickness (volume heat flux) on the temperature rise is nearly linear. It means that thin wall pipe has higher temperature rise under the same inner surface heat flux.

Figure 7. Relationship between highest temperature rise and volume heat flux
Considering the impact of volume heat flux, it has to be kept constant when the influence of pipe diameter is studied. The inner diameter is changed in the range of 6-20mm, and the thickness is chosen to make sure that the volume heat flux is 400MW/m³. Another constant is the size of dry area, whose width and length are both 10mm. In figure 8, the temperature rise increases with the decrease of inner diameter. However, this impact will reduce if the inner surface is much bigger than dry area. The thin pipe will face higher temperature rise for the same dry area.
1.4. Shape of pipe

Different from round pipe, square pipe is asymmetric in circumferential direction. In order to reflect the asymmetry the dry area whose length and width are both 10mm is placed at the centre of one side and at the corner separately. Hence, this case is much severer than ever because the dry area is formed in an instant. The surround reference temperature is supposed as 300°C. In the initial moment the temperature distribution is uneven because more heat will be accumulated in the corner. As shown in Figure 9, the highest temperature rise is 285K when the dry area is placed in the centre, and the value is 337K when the dry area is placed at the corner.

1.5. Thermal stress

After studying the process of temperature rise under several condition, it is known that there must be a large enough area of heat transfer deterioration region and lasting for quite a long time, so that the wall temperature can rise to the “burning” point (melting point), which is usually thought to be more than
1200°C. So thermal stress should be analysed to check if the pipe will be damaged before “burning” point. The thermal stress is calculated by Workbench module Static Structural[11]. It should be mentioned that the reference temperature is supposed as the initial temperature when there is no dry area, and the fixed support is loaded on both sides of pipe. Taking the temperature field of final stable state in figure 4 the highest temperature rise is just 330K, which is lower than “burning” point. Figure 10 shows its maximum shear stress. The maximum value is 465MPa, which has exceed the allowable stress of normal steel (for 304 stainless steel the value is 137MPa). According to the maximum shear strength theory, the pipe wall will be damaged by the thermal stress. So the most cases of the pipe wall damage is due to thermal stress instead of traditional statement “burning”.

Figure 10. maximum shear stress

Conclusions
In this paper under the assumptions that beyond the actual situation the temperature rise of pipe is analysed. The results are not in line with traditional analysis expectations. It looks that the CHF tested in many experiment is not the heat flux value, which can makes the temperature rising until melting. The CHF tested in many experiment should be the heat flux value which can make the pipe break by additional thermal shear stress. And the CHF phenomenon is not an instantaneous transient. The speed of temperature rise is not as fast as expected. It will last a long time. According to the calculation results the following conclusions can be drawn.

1. Growth rate of dry area has little influence on the process of temperature rise. The highest temperature rise is directly dependent on the size of dry area.
2. The volume heat flux affects the temperature rise almost linearly.
3. The pipe wall damage is due to thermal stress instead of traditional statement “burning”.

All of these will be tested in the next pool boiling experiment in the second half of this year.

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