INVESTIGATION OF CRITICAL HEAT FLUX BEHAVIOR IN TIGHT ROD BUNDLES WITH AND WITHOUT WIRE SPACER

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Abstract: In order to investigate the coolability of tight rod bundle with wire spacer, the study on CHF behavior was conducted by means of experiment for boiling two-phase flow in three-pin tight rod bundle with and without wire spacer. The effect of wire spacer and pitch to diameter ratio on CHF were considered. The experiment was performed with the mass flux ranged from 250 to 430 kg/m^{2}s, the inlet temperature from 70 to 92^{o}C at atmospheric pressure. The results show the enhancement of CHF by wire spacer. Besides, the CHF was also increase by decrease the pitch to diameter from 1.18 to 1.10 under the same flow rate condition.
Keywords: *Tight rod bundle, Wire spacer, Critical heat flux, Pitch to diameter ratio, Two-phase flow.*

1. INTRODUCTION

One of the most important requirements in the fourth generation nuclear reactors is the sustainability of the use of nuclear energy. It is known that the liquid metal-cooled fast reactors (LMFR) that have the breeding ratio higher than unity meet the requirement of sustainability. However, the LMFR poses some unique design problems compared to the light water reactors which have been commercialized and operated for long years. On the other hand, tight lattice core with smaller coolant volume ratio compared with a normal core could have a higher conversion ratio nearly equal to unity even in light water reactors (LWR), particularly in boiling water reactors (BWR). The use of wire spacers is more suitable for the tight lattice core than the use of grid spacers. However, from thermal hydraulic point of view, the coolability or heat removability is one of the key issues for the feasibility of the tight lattice core with the wire spacer. The most crucible feature of coolability is the critical heat flux (CHF) of the fuel rods in the BWRs. There have been numerous studies on CHF so far. Nevertheless, the studies on the CHF of the tight lattice core with wire spacers are still few. In case of thermal-hydraulics for nuclear reactor, there have been a lot of studies on the CHF data base for fuel channels with grid spacers, but not in case of wire type. Thus, the critical heat flux or burnout phenomenon in tight lattice core is one of the most important studies for such kind of reactor.

Cheng & Muller (1998) performed the CHF experiment in a hexagonal tight rod bundle. The rod bundle consisted of seven rods with the rod diameter d of 9.5 mm, the pitch p of 10.9 mm and p/d=1.15. They found that the CHF in the hexagonal rod bundle with wire spacers was higher than that with grid spacers at low quality conditions but in a high quality region, the CHF were nearly the same in the bundles with both types of spacers. The experiment was performed by using Freon-12 because of its low latent heat and low critical pressure, and CHF in water flow was evaluated from the results of Freon-12 by using the fluid-to-fluid scaling law of Courtaud, et al.(1988). However, the dimensions of the wire spacer such as wire diameter and wire pitch were not described. Therefore, it is difficult to confirm and use the experiment data to design the tight lattice core for nuclear reactor. Because of the indistinctness in wire parameter, the effect of wire spacer on CHF was not clear.

Diller, et al. (2009) performed the thermal-hydraulic analysis for wire wrapped fuel assembly in PWR cores, and it was concluded that the advantages of fuel assembly with wire spacer type over grid spacers were significant reduction in pressure drop and an increase in CHF. Through this study, it can be seen that the power of the reactor core could be upgraded by using wire spacer instead of grid spacer. Nevertheless, this research was only based on simulations for the fuel bundles of PWR without considering the effect of boiling phenomena.

Celata, et al.(1994) conducted the CHF experiments for subcooled water flow boiling in the tube in which helically coiled wire was inserted. The diameter and the axial coiling pitch of the wires were 1 mm and 20 mm, respectively. The author presented the increases of CHF and pressure drop for the tube with helically coiled wires compared with the smooth tube without the wires. The CHF increased by up to 50% and the pressure drop also increased by up to 25%. Since the CHF experiment was performed in a round tube with helically coiled wire inserted inside, the phenomena was different from those in a flow in an annular channel where a wire was wound around a central heater pin. However, by reviewing this study, it can be seen that the spiral flow due to the effect of wire could enhance CHF.

In order to consider about the effect of wire spacer, the wire shape is also needed. Raza and Kim (2008) investigated the effect of wire spacer shape on thermal hydraulic performance. Three different cross sectional shapes of wire spacer were chosen: circle, hexagon, and rhombus. The study was performed by using a computer program to analyze the pressure drop, temperature and heat transfer of the rod bundle with three different shapes of wire spacer. It was shown that the circular shape of wire spacer had the best performance in overall pressure drop, maximum temperature and uniformity of temperature in the rod bundle compared with the other two shapes. By reviewing this study, the circular shape of wire spacer was selected for our study in order to be able to get the best thermal hydraulic performance and could be useful for the reactor design.

Moreover, the fuel bundle with wire spacer has advantages with respect to not only thermal-hydraulic performance but also nuclear performance. Olander (2009) studied hydride fuel with wire spacer, and showed that the fuel assembly could have good nuclear performance and could reduce the core size.

From the review of the studies on the effects of the wire spacer mentioned above, it can be seen that wire spacer has some interesting advantage, particularly in thermal-hydraulic performance. Therefore, the main objectives of the present study are to investigate the CHF behavior in three-pins bundle with wire spacer under boiling two-phase flow condition and to clarify the effect of some factors such as mass flux, quality and geometry parameter on CHF. Moreover, this study is focusing on the effect of wire on CHF.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

2.1 Experimental Apparatus

The experimental apparatus is shown in Fig.1. It consists of the water tank, the circulation pump, the pre-heater, the orifice flow meter, the three-pins bundle CHF test section, the condenser and the air cooler. The water was circulated from the water tank through the circulation pump and the pre-heater and enters the test section. Steam after going through the test section is condensed prior to flow back to the water tank. The orifice flow meter was at first located in the downstream of the pre-heater. In case of inlet temperature near the saturation temperature, a small amount of steam bubbles flowed out of the pre-heater into the flow meter. In order for the steam bubbles not to affect the measurement of water flow rate, the location of the orifice flow meter was moved to the upstream of the pre-heater.

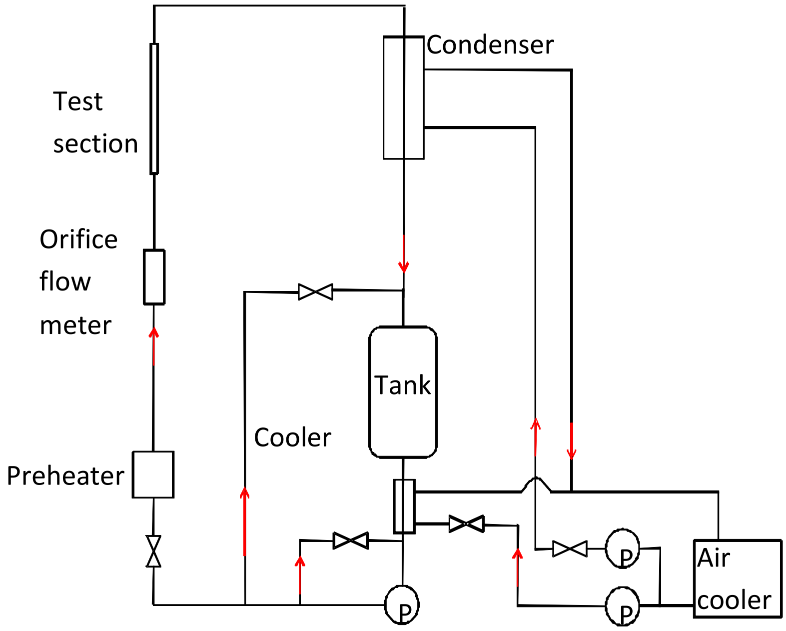

Fig.1 Experiment apparatus

Three-pin bundle test section was made from three stainless steel heater and assembled as the triangular arrangement as shown in Fig.2 . The outer diameter and the length of each heater pin was 4.57 mm and 400 mm, respectively. It was connected to the copper electrodes at both ends by silver soldering. The direct Joule-heating for the heater pin provided an uniform heat flux on the heater pin surface. The maximum power and current of the power in this experiment were 12kW and 630A, respectively. The spacer was electrically insulated from the heater pin by using Teflon tube.

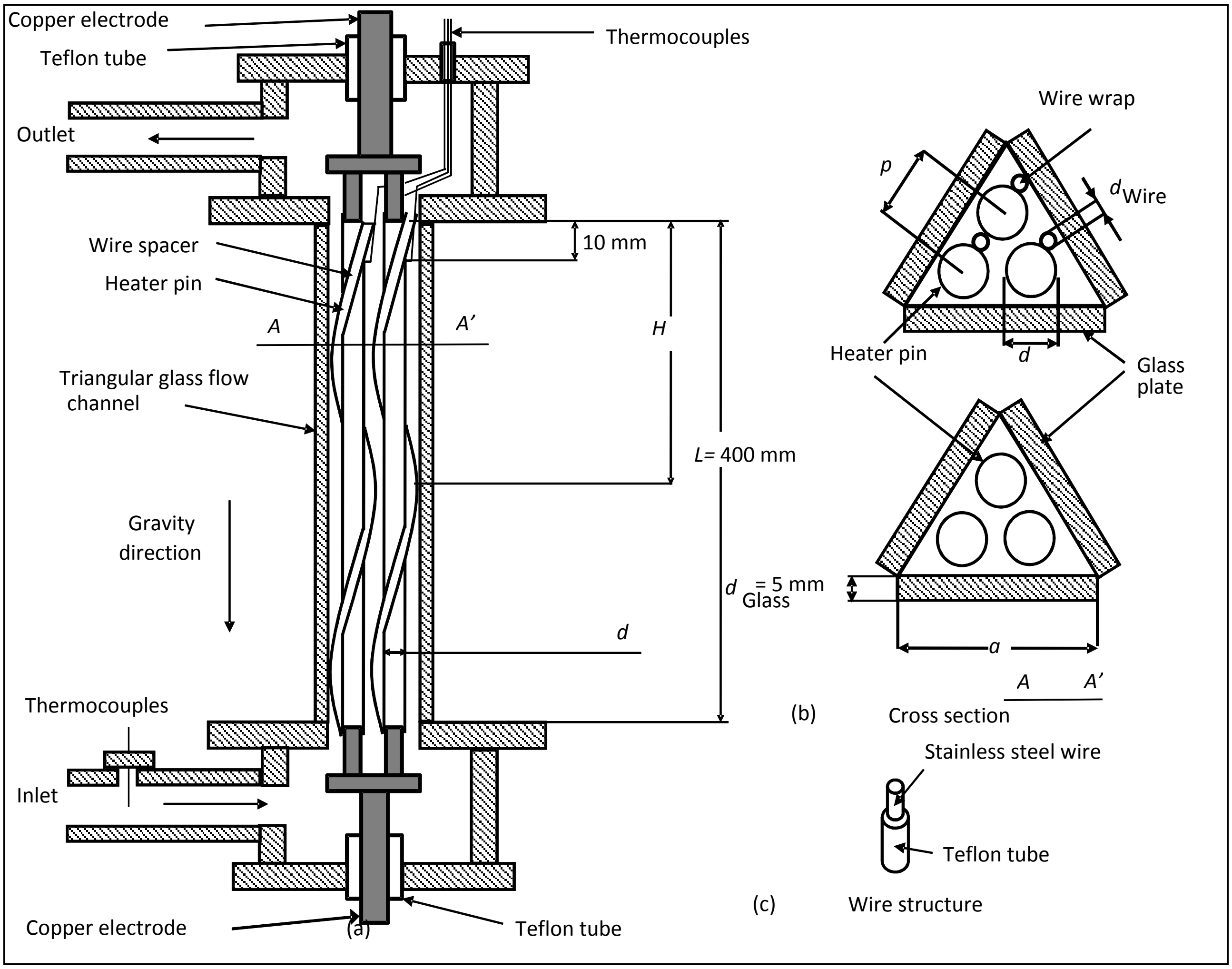

Fig. 2 Test section: (a) test section; (b) cross section of the flow channel with wire and without wire spacer; (c) wire structure.

Pitch was defined as the distance between the centers of two adjacent pin. In this study, the pitch, *p*, of 5 mm and 5.4 mm were chosen. Thus, the pitch to diameter ratio, p/d, of 1.10 and 1.18, respectively. In the case of p/d of 1.18, the wire spacer was a stainless steel wire coated by Teflon tube with an outer diameter d_w of 0.76 mm. On the other hand, in the case of p/d of 1.10, the wire spacer was made by a Holmal coated wire which had an outer diameter, d_w of 0.4 mm. The Holmal coated wire was chosen to be able to design the tight-rod bundle with the gap size of 0.5 mm. The axial pitch of with, *H* is 200 mm.

In order to detect a sudden rise of temperature on the heater pin surface at the CHF condition and quickly shutdown the heating power, Type K thermocouple elements with diameter of 100 μm were used for the surface temperature measurement. The ends of the thermocouple elements were spot-welded to the heater pain surface to be hot junctions at the positions of 10 mm upstream from the downstream end of the heated length, being marked as T1, T2 and T3, respectively.

3. RESULTS AND DISCUSSION

3.1 Effect of Wire Spacer

The results of CHF with and without wire spacer in three-pin bundle are shown in Fig.3. The CHF values with wire spacer were higher than that without wire spacer. In addition, the enhancement was more significant at the low quality region. The reason for the enhancement of CHF in the low quality region can be explained by the rise of turbulent mixing by wire spacer. The enhancement of turbulent mixing lead to the increase of bubble removal from the heated surfaces. On the other hand, due to the existence of wire spacer, the spiral flow as a vortex was created at the center of the flow channel. Therefore, the centrifugal force caused by the spiral flow would bring the droplets from the center of flow channel to rewet again the heated surface which lead the enhancement of droplet deposition rate. Hence, the CHF was increased.

On the other hand, at higher vapor quality region, the CHF was nearly the same in the cases of bundle pins with wire and without wire spacer. At higher vapor quality region, the liquid film flow becomes thinner compared with it in the lower quality region in the high quality region. Therefore, the liquid film would be broken easier due to the existence of the wire spacers, which tend to the dry-out more easily occur. Moreover, because of the enhancement of the boiling heat transfer rate in the high quality region than in low quality region, the disturbances of the bubbles become higher and tend to break the liquid film, which leads to the decrease of CHF values.

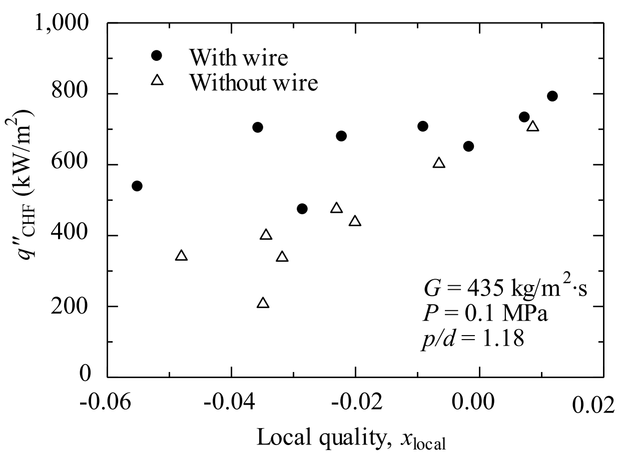

Fig. 3 Critical heat flux in bundle with and without wire spacer.

3.2 Effect of Pitch to Diameter Ratio

The comparison of CHF between two different values of p/d under the same water flow rate condition is shown in Fig.4. It can be seen that, the CHF values in the case of p/d of 1.10 were much higher than that in the case of p/d of 1.18 under the same mass flow rate condition.

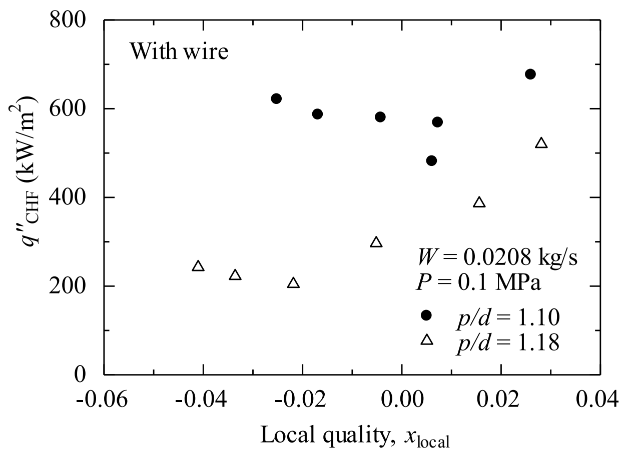

Fig. 4 CHF of difference values of *p*/*d* with the same flow rate condition.

The reason for the enhancement of CHF values can be explained by the increase of mass flux. The flow area was smaller in the case of *p/d* of 1.1 than that in the case of *p/d* of 1.18. Therefore, under the same flow rate condition, the mass flux was higher in case of flow channel which has the *p/d* of 1.1 in comparison with that which has the *p/d* of 1.18. Thus, the coolant velocity would higher in case of *p/d* of 1.1 than that in case of *p/d* of 1.18, which leads to the enhancement of heat transfer coefficient and coolability in tighter rod bundle.

4. CONCLUSIONS

The CHF behavior was in tight rod bundle was investigated by means of experiment for three-pin bundle with and without wire spacers. The conclusions are as follows:

(1) The CHF values in tight rod bundle were enhanced with wire spacer compared with it without wire spacer under constant mass flux condition. At the low quality region, the enhancement was more significant. Therefore, the coolability of tight lattice core could be optimized by using wire spacer.

(2) Under the same flow rate conditions, the CHF values increased when decrease the pitch to diameter ration from 1.18 to 1.10.

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NOMENCLATURE

d	outer diameter of heater pin
d_w	wire diameter
G	mass flux
H	axial pitch of wire spacer
L	heated length
p	pitch
P	pressure
W	mass flow rate
x_{local}	local quality

NGHIÊN CỨU VỀ THÔNG LƯỢNG NHIỆT TỚI HẠN CHO BÓ NHIÊN LIỆU CÓ KÍCH THƯỚC Ô MẠNG NHỎ CÓ HOẶC KHÔNG CÓ LƯỚI GIẰNG DẠNG DÂY CUỐN

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Tóm tắt: Nhằm đánh giá khả năng tải nhiệt của bó nhiên liệu có kích thước ô mạng nhỏ với lưới giằng dạng dây cuốn, nghiên cứu thực nghiệm về thông lượng nhiệt tới hạn đã được triển khai. Thực nghiệm về thông lượng nhiệt tới hạn cho bó nhiên liệu bao gồm ba thanh đốt nhiệt với kích thước ô mạng nhỏ có hoặc không có dây cuốn được tiến hành dưới điều kiện dòng chảy sôi hai pha. Tác động của dây cuốn và tỷ số giữa khoảng cách đường nối tâm và đường kính thanh nhiên liệu, lên giá trị thông lượng nhiệt tới hạn cũng được đề cập đến trong nghiên cứu này. Thí nghiệm được thực hiện trong môi trường áp suất khí quyển với dải giá trị thông lượng dòng từ 250 đến 430 kg/m^2s, giá trị nhiệt độ đầu vào từ 70 đến 92^oC. Kết quả thu được cho thấy giá trị thông lượng nhiệt tới hạn tăng khi sử dụng lưới giằng dạng dây cuốn. Bên cạnh đó, giá trị thông lượng nhiệt tới hạn cũng tăng khi tỷ số giữa khoảng cách đường nối tâm và đường kính thanh nhiên liệu giảm từ 1.18 xuống 1.10 ở cùng điều kiện về tốc độ dòng khối.

Từ khóa: Bó nhiên liệu có kích thước ô mạng nhỏ, Lưới giằng dạng dây cuốn, Thông lượng nhiệt tới hạn, Tỷ số giữa khoảng cách đường nối tâm và đường kính thanh nhiên liệu, Dòng hai pha.