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《Original》

Reflood Experiments with Horizontal and Vertical Flow Channels

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Abstract

The investigation of the fuel cladding temperature behavior and heat transfer mechanism during the reflooding phase of a LOCA plays an important role in performance evaluation of ECCS and safety analysis of water reactors.

Reflooding experiments were performed with horizontal and vertical flow channels to investigate the effect of coolant flow channel orientation on rewetting process. Emphasis was mainly placed on the CANDU reactor which has horizontal pressure tubes in core, and the results were compared with those of vertical channel. Also to investigate the rewetting process visually, the experiments by using a rod in annulus and a quartz tube heated outside were performed.

It can be concluded that the rewetting velocity in horizontal flow channel is clearly affected by flow stratification, however, the average rewetting velocity is similar to those in vertical flow channel for same conditions.

요 약

냉각재상실사고의 재관수 단계중 연료봉 피복재의 온도거동 및 열전달 기구를 파악하는 것은 비상노심냉각계통 및 원자로의 안전성해석에 중요하다.

냉각재유동채널의 방위가 rewetting과정에 미치는 영향을 연구하기 위하여 수직 및 수평 유동채널을 이용한 실험을 수행하였으며, 노심이 수평압력관으로 구성되어 있는 CANDU원자로에 관한 실험을 중점적으로 수행하여 그 결과를 수직채널의 결과와 비교 하였다. 또한 rewetting현상을 육안관찰하기 위해 환상형 테스트부 및 외부에서 가열되는 석영관을 사용하였다.

실험결과로써 수평채널에서의 rewetting 속도는 유동의 층상 현상에 크게 영향을 받으나 그 평균값은 수직채널의 경우와 큰차이없음을 알 수 있었다.

Nomenclature

- G : flow rate, g/sec
- K : clad thermal conductivity, w/cm,°C
- ρ : clad density, g/cm^3
- C : specific heat, J/g°C
- D : rod diameter, cm
- T_c : coolant temperature, °C
- T_s : saturation temperature, °C
- T_o : rewetting temperature, °C
- T_w : wall temperature, °C
- ϵ : clad thickness, cm
- R : pipe inside radius, cm
- u : rewetting velocity, cm
- U^* : dimensionless rewetting velocity, $\frac{\rho C \epsilon U}{K}$

I. Introduction

The ability to predict the rewetting phenomena of hot surface is of considerable interest in nuclear reactor safety analysis. In the event of the LOCA, it is expected that the depressurization of the system and the coolant loss in the core would be followed by dryout of the fuel rods. The residual heat generation and stored heat in the fuel element would cause the clad temperature of the fuel rod to rise unacceptably. In such an emergency, rewetting of a hot surface can be achieved by spray cooling(BWR)[1], by bottom flooding(PWR)[2], or by horizontal flooding(CANDU-PHW)[3]. These cooling processes can exhibit considerably different physical phenomena, since the flow pattern can be different,

In spite of the numerous analytical[4],[5] and experimental[6],[7] studies the thermal behaviour of the core during reflood phase is still the central question of the LOCA. A number of reflood review papers have been presented in the literature such as Yadigaroglu[8], Butterworth and Owen[9], Sawan and Carbon[10]. These research efforts are concerned with vertical flow channels.

The horizontal channels in the CANDU-PHW reactors are subject to asymmetrical effects by the gravitational field. The asymmetrical effects are not significant in normal operating conditions but can influence the behaviour in reflood process where the mass flow decreases and temperature rises. Very little information is available on horizontal flow channels. Therefore, simple experiments were performed with vertical and horizontal heated tubes to investigate the effect of coolant flow channel orientation on rewetting process under well-defined experimental conditions. Visual observation of rewetting phenomena in the annular-geometry and in a transparant quartz tube was also discussed. These informations are needed for various codes modeling the rewetting process during the LOCA.

II. Experimental

Fig. 1 shows the schematic diagram of the main test loop which is used to investigate the rewetting phenomena for both vertical and horizontal flow channel. The detail description of the loop was reported elsewhere[11]. The test section was a 1.8m long stainless steel 304 tube with an outside diameter of 19.5mm and a wall thickness of 0.89mm. The tube was electrically heated by attaching power leads to the 78mm diameter, 8mm thick end stainless steel flanges. Asbestos wrapped, chromel-alumel thermocouples were spotwelded onto the outside wall of the test section, 20cm spacing in axial direction and 4 circumferential points at each spaces for monitoring and recording the wall temperature. Insulation was provided by wrapping the asbestos tape around the test section. To avoid bowing of the test section due to thermal expansion and contraction during horizontal flooding, outlet part of the test section was connected to the U-shaped flexible hose and a support pad was provided around the insulator of the test section.

To observe the flow pattern during rewetting process another test loop was arranged such that a indirect heater rod as a test section was housed in transparent pyrex tubes as shown in Fig. 2. The indirect heater rod was made of double stainless steel tubes with Ni-Cr filament as a heating element insulated by MgO. Two stainless

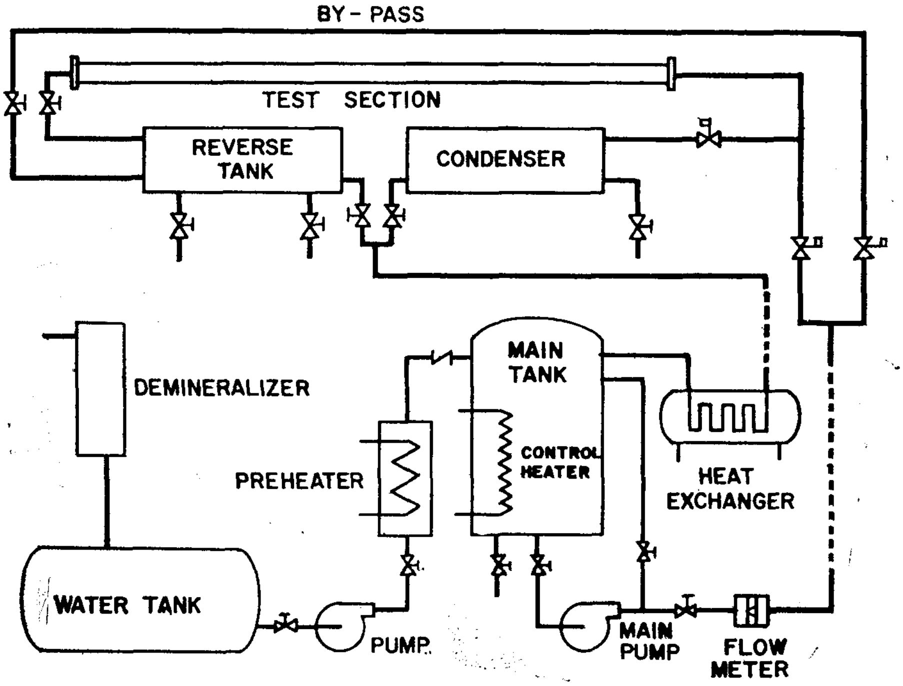

Fig. 1. Schematic Diagram of Test Loop

steel sheath chromel-alumel thermocouples were embedded between the stainless steel tubes (Fig. 3). The heater rod was a 1.2m long with a heated length of 60cm and maximum linear power of 1.25kw/m. And the test section was replaced by transparent quartz tube which was heated outside by winding the Ni-Cr filament around the tube to get the information of and to observe visually the rewetting phenomena in a heated tube. And the experimental methods and conditions were almost same as those of the rod in annulus.

Each experiment was done at atmospheric pressure and a constant flooding rate. The test procedure was as follows. The main tank was filled with demineralized water and this water was heated up to a desired tempera-

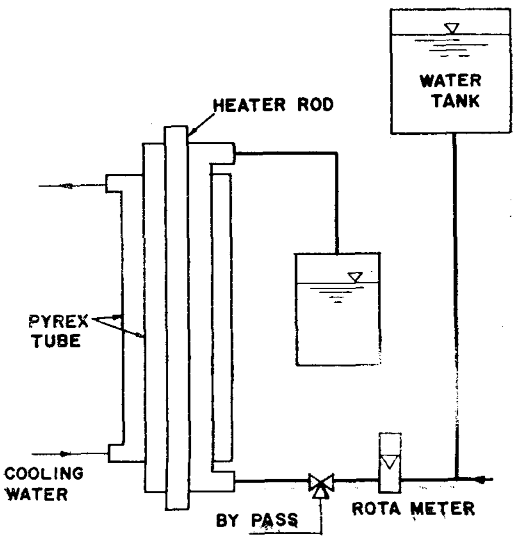

Fig. 2. Schematic Diagram of Apparatus for Annular Type Experiments

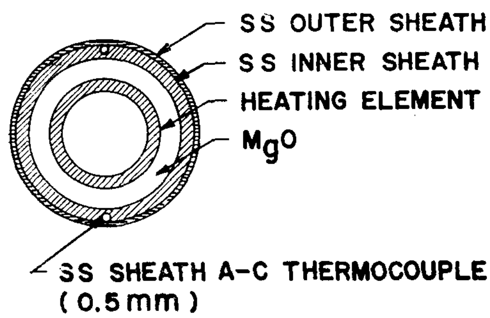

Fig. 3. Idealized Presentation of Heater Rod

ture. Then flow rate was adjusted by a rota meter through the bypas line. The adjusted flow rate divided by flow area of the test section was defined as a flooding rate. After setting the flooding rate, the test section was heated up to the initial temperature by 5KVA, max. 1000 ampere, D.C power supply. The water injection into the test section was started by opening the quick-opening valve after experimental conditions were obtained. At the same time high speed data acquisition system and strip chart recorder were operated to detect the temperature variations. The power to the test section was either maintained or switched off during injection according to experimental conditions. The main output of an experiment is the temperature-time traces of the test section. The rewetting velocity would be estimated by the methods decribed in Ref. 11.

III. Results and Discussions

Parameters which may influence the rewetting process are flooding rate, wall temperature, heat generation rate, and channel orientation. The ranges of parameters considered are given in Table 1.

Table 1. Ranges of Parameters

Flooding Rate	0.25—40cm/sec
Wall Temperature	300—700°C
Coolant Subcooling	10—80°C
Test-Section Orientation	Vertical, Horizontal
Wall Heat Flux	up to 15W/cm^2

1. Visual Observation of Rewetting Phenomena

Rewetting can be defined by the change in heat transfer regime during the cooling process of hot surfaces from film to nucleate boiling. In case of film boiling heat is conducted from the hot surface to the fluid mainly through a vapor film covering the hot surface. When the hot surface is cooled down to a temperature where direct contact between fluid and surface takes place, nucleate boiling is then possible. In this case the surface is said to be quenched or rewetted. This temperature is called rewetting temperature, also called as the Leidenfrost, calefaction, sputtering, quenching, temperature corresponding to the minimum film boiling heat flux.

It was observed in annular test section that the rewetting front was clearly defined, and was almost uniform around the circumference of quench zone when the flooding rate was less than 3cm/sec. This implied that nearly uniform distribution of coolant phase and rewetting velocity were maintained. However, when the flooding rate was faster than 3cm/sec, the vertical position of the rewetting front was circumferentially not uniform as shown in Fig. 4. So it was assumed that surface condition seemed to make the rewetting front not uniform. But since such effect was very localized, average value of rewetting velocity tended to remain constant.

As the flooding rate increase, distinct flow patterns were formed, as shown in Fig. 5 together with corresponding wall temper-

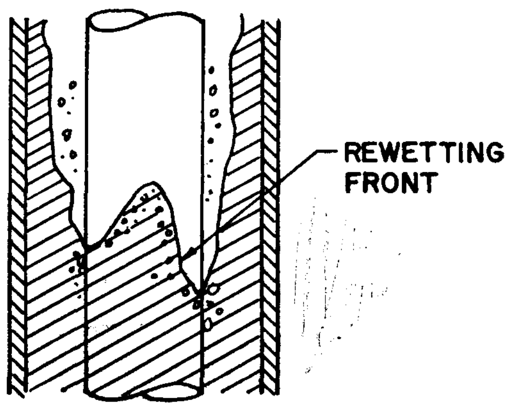

Fig. 4. Showing of the Rewetting Front which is Circumferentially Nonuniform

ature. It was observed that only steam flew up just after coolant contacted with the hot surface. After enough steam was generated such that entrainment of water was possible, liquid droplets were seen to dance up and down. This entrained droplets would hit the hot surface and bounce back as a result of rewetting phenomena. However, the droplets acted as heat sinks for surface radiation and provided very good local cooling during the short periods of contact with the hot surface. The flow boiling at this time was defined as dispersed flow boiling.

Secondary observed flow pattern was film boiling. Film boiling is the boiling mode in which a continuous blanket of vapor is generated and maintained to isolate the liquid from the hot surface. In film boiling region, it was found that unstable and stable film boiling took place. In case of unstable film

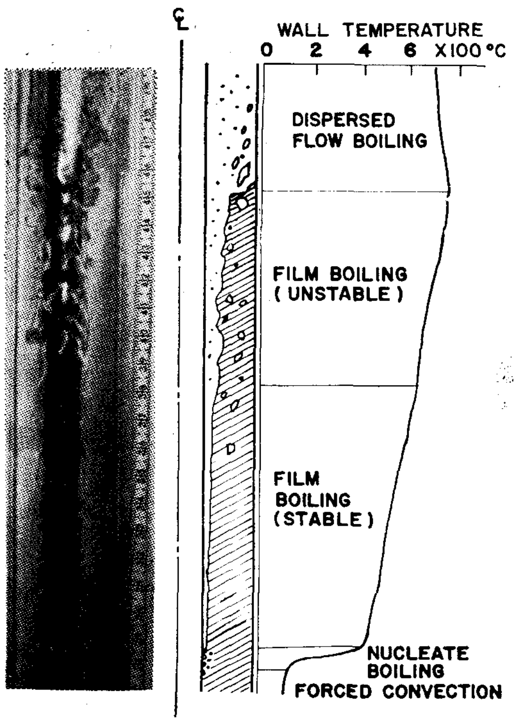

Fig. 5 Flow Pattern in Bottom Flooding with Corresponding Wall Temperature

boiling film thickness was not clearly defined, and film was not continuous. In case of stable film boiling, film thickness was almost constant (~2mm) at the same conditions, but film boiling length which was defined as the distance between the rewetting front and the water front was increased up along the heater rod.

Nucleate boiling was observed at the end of film boiling region. Near the rewetting front very violent boiling took place at the short small distance(~1mm). After nucleate boiling the temperature of the heater rod was decreased by liquid single convection. The transition between film and nucleate boiling becomes important when calculating the rewetting velocity.

In order to observe the rewetting phenomena in a heated tube a quartz tube heated up to 600°C was used. Flow pattern observed in a vertical quartz tube was similar to those in annular test section. Injected water could not wet the quartz tube at downstream of the rewetting front and a liquid column was formed in the center of the tube. When the length of a liquid column became a certain value, the steam velocity breaked up the liquid column into large droplets, these droplets began to dance up and down and sometimes flew to the top of the tube with a rapid progress and hit the tube like jet impingement. When the wall temperature fell down to the rewetting temperature the water began to wet the wall, so rewetting occured. Similar observation in a vertical quartz tube was done in ref. 12.

When the quartz tube was placed horizontally, the flow pattern was sensitive to change of the flooding rate. At the low flooding rate the flow was stratified and never touched the top of the tube. At the high flooding rate the flow pattern of rewetting was shown in Fig. 6. Film boiling was formed at the bottom of tube, but the film thickness was very small compared to those of vertical. When the water front of the bottom moved to forward very fast, the water front of the top moved to backward by back pressure. This implied that the rewetting velocity in a horizontal tube was not constant along the tube for same experimental conditions.

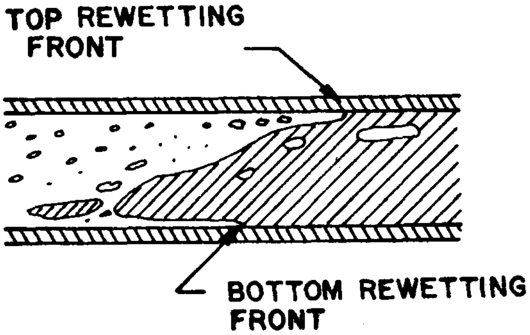

Fig. 6. Rewetting Phenomema in the Transparent Horizontal Quartz Tube

2. Effect of Wall Temperature

In general, analytical study[5] assumed that the wall temperature in the unwetted region, i.e., downstream of the rewetting front, was constant throughout the rewetting process. This meant that the rewetting velocity was constant. However, in all cases, axial wall temperature was not uniform as shown in Fig. 7. Fig. 7 shows that end effects could be significant in experimental works. Therefore the results from only middle portion of the test section, where a reasonably uniform temperature remained at the beginning of a test, were considered. In the bottom flooding the effect of precursory cooling by two phase flow in unwetted region was considerable and the temperature of unwetted region decreased significantly by precursory cooling. This is clearly seen in Fig. 7. Therefore it could be expected that the rewetting velocity is not constant.

However, as the wall temperature was decreased by precursory cooling, the rewetting velocity along the test section was not increased because coolant temperature was increased as it moves along the test section such that subcooling effect on the rewetting velocity was decreased. It was observed by experiments that rewetting velocity increases as subcooling increases. So the assumption of the constant rewetting velocity along the vertical channel is quite reasonable, especially for the case of a low initial wall temperature with a low flooding rate.

When the coolant was injected into the horizontal test section, as we expected, phase

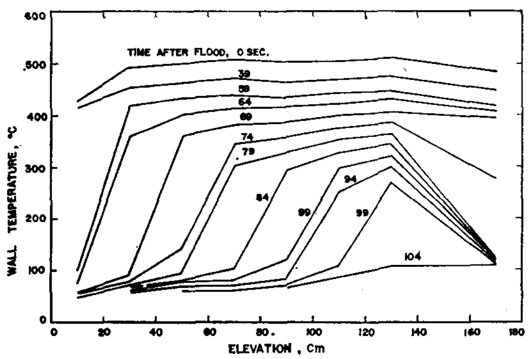

Fig. 7. Axial Wall Temperature Profile in Vertical Flow Channel(Flooding Rate; 10cm/sec)

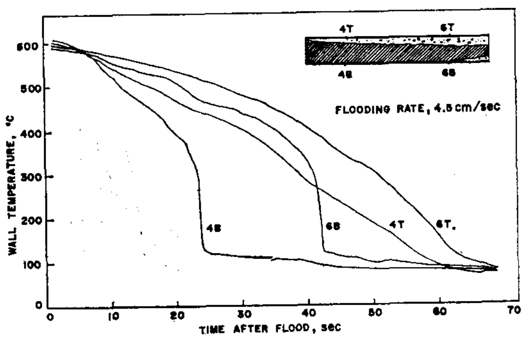

Fig. 8. Temperature-time Trace of Horizontal Flow Channel for Low Flooding Rate

distribution and the temperature distribution around the test section circumference was not uniform due to the gravitational force and different heat transfer mechanism. As stated before, at the low horizontal flooding rate flow stratification was formed such that the water tended to the bottom of the test section while the steam with entrainment moved to top. Flow stratification could be seen on the temperature-time traces at 4.5cm/sec flooding rate (Fig.8). Even the bottom region at thermocouple 4B was rewetted, top region at thermocouple 4T was not contacted with coolant and cooled down only by precursory cooling and conduction.

Fig. 9 shows that at the high flooding rate bottom and top region were rewetted with a time delay. But this time delay was changed along the test section.

Our previous experimental studies[11] in bottom flooding showed that the rewetting velocity was nearly constant with time, with an approximately linear relation with the reciprocal of the wall temperature. However, the trend that rewetting velocity increase with decrease in the wall temperature was not found in the horizontal flow channel as shown in Fig. 10. As previously described the reason was thought to be due to flow pattern variation which affects the rewetting velocity at top and bottom in the horizontal tube.

3. Effect of Flooding Rate

Our previous report[11] showed that for all cases of the wall temperatures the rewetting velocity increased linearly as the flooding rate increase. Effect of the flooding rate on time to rewet was analyzed in Fig. 11 and 12, where rewetting time was plotted versus the flooding rate. The rewetting time increased with decrease in flooding rate for the whole range but more sensibly for lower flooding rates. This was because the increase in the flooding rate may increase the heat transfer coefficient and precusory cooling of the unrewetted region of the hot surfaces.

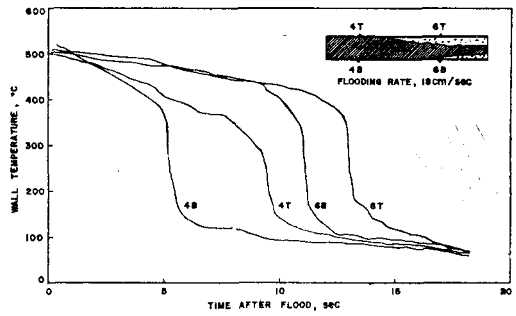

Fig. 9. Temperature-time Traces of Horizontal Flow Channel for High Flooding Rate

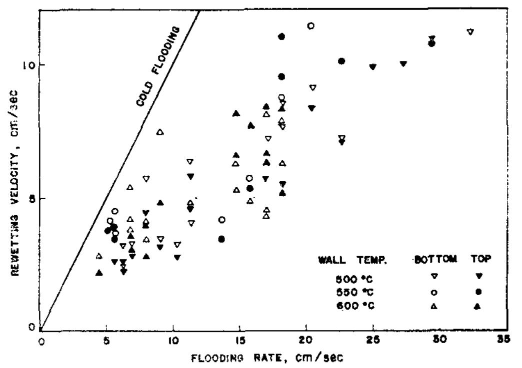

Fig. 10. Rewetting Velocity of Top and Bottom Side in Hori ontal Flow Channel

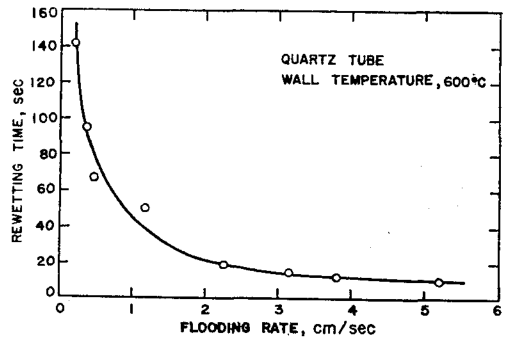

Fig. 11. Effect of Flooding Rate on Rewetting Time

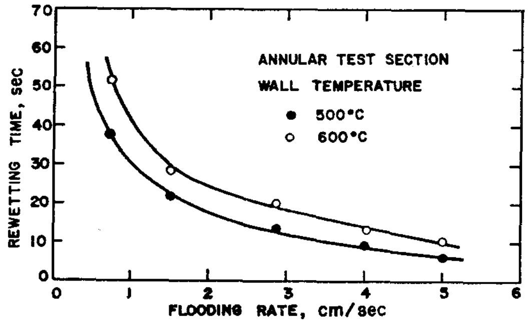

Fig. 12. Effect of Flooding Rate and Temperature on Rewetting Time

Fig. 13 shows that when the flooding rate was less than 3cm/sec in bottom flooding, the rewetting velocity was not less than the flooding rate. It could be expected that the coolant wetted the wall above the water front by annular flow. Similar phenomena were found in a transparent quartz tube through visual observation.

Fig. 14 shows the effect of flow orientation. It was cleary found from experimental works that the rewetting velocity for vertical flow increased with increase in flooding rate, when other conditions were kept constant. For horizontal flow, however, the rewetting velocity was not increased linearly with flooding rate, but except some data the sams trend as the case of vertical flow was obtained. It may be thought that the

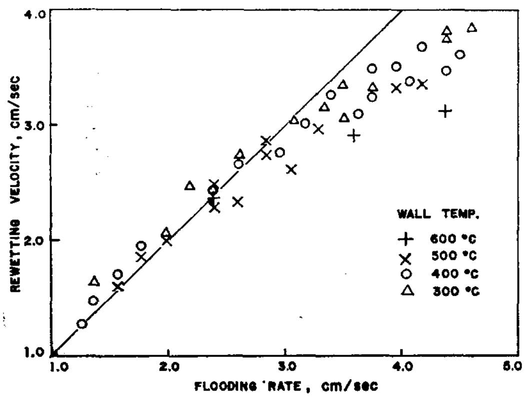

Fig. 13. Effect of Wall Temperature in Vertical Flow Channel at Low Flooding Rate

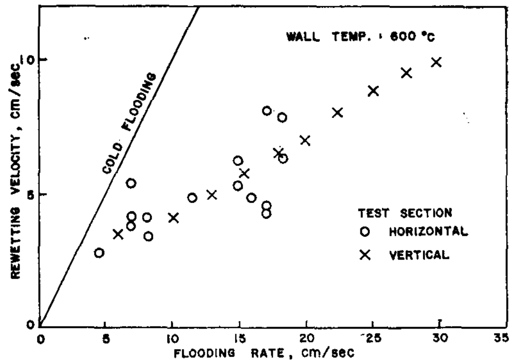

Fig. 14. Effect of Flow Orientation on Rewetting

average rewetting velocities in a horizontal flow channel were close to those in a vertical flow channel for same conditions. This is not in agreement with the results reported in ref. 13.

4. Effect of Heat Generation Rate

All the results presented so far are those obtained from the tests where the power input to the test section was switched off at the beginning of the test, t=o; i.e., no heat generation during the rewetting process. Fig. 15 shows the rewetting velocities at different power inputs during the rewetting process in a vertical channels.

For the range of flooding rate (11.3 to 22.5cm/sec) studied, the rewetting velocity decreased with increase in power input. Since higher heat generation during rewetting process should produce a higher wall surface temperature and increase the heat content to be transferred, it should cause the rewetting front to advance more slowly. Fig. 15 also shows a critical flooding rate at which the hot surface at a certain amount of heat flux could be wetted.

5. Correlation of Experimental Data

Recently many investigators have proposed the analytical solutions of rewetting process and have correlate their solutions with the

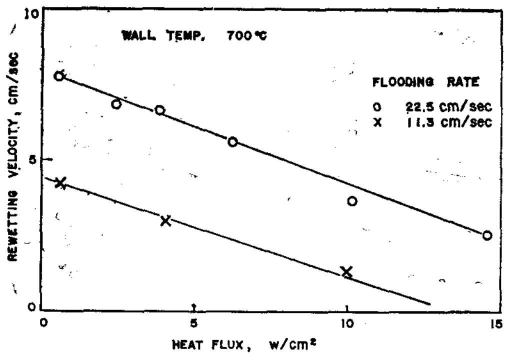

Fig. 15. Effect of Power Input during Rewetting Process in Vertical Flow Channel

experimental data. But upon now there is no proper correlation exactly inter-relate the rewetting temperature and heat transfer coefficient because the physical phenomena of rewetting process were not fully understood yet.

In this paper the rewetting temperature was assumed to be constant at 260°C and the heat transfer coefficient to be the function of flow rate, coolant subcooling, and wall temperature.

Fig. 16 shows the results of present study with vertical tube test section in comparison to other's. In this figure, U* represents the dimensionless rewetting velocity, $\frac{\rho C \epsilon U}{K}$ and (T_S-T_C) represents the coolant subcooling. Present results are not much different from other's as we can see in Fig. 16.

We also compared the present results from annular test section with the theory of Duffey and Porthouse[5] as shown in Fig. 17 and we can see that present results are in agreement with the theory of Duffey and Portהוו e.

No attempt was made to compare the experimental results from the horizontal test section with analytical models, since there is no credible analytical model for the horizontal flow.

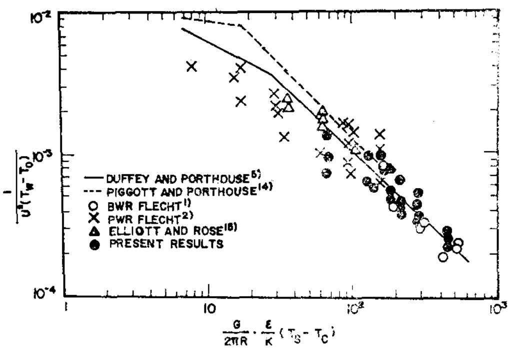

Fig. 16. Correlation of Rewetting Data

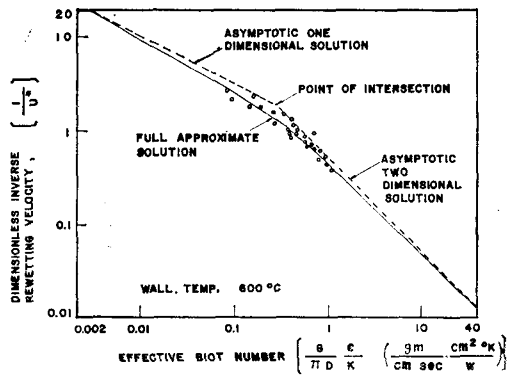

Fig. 17. Comprison of Theory with Experiments

IV. Conclusions

Experimental studies on the rewetting process of PWR and CANDU reactors were carried out with the test sections such as a stainless steel tube, a heater rod in annulus, and a quartz tube. Emphasis was placed on the visual observation of rewetting phenomena and on the particular feature of CANDU reactor, which has a horizontal pressure tube, that is, the effect of coolant flow orientation on the rewetting process. It can be concluded from the experimental studies that the rewetting velocity is clearly affected by flow stratification due to the channel orientation with respect to the gravitational field, however, the average rewetting velocities in horizontal flow channel are similar to those in vertical flow channel for same conditions.

References

1. J.D. Duncan and L.E. Leonard, "Emergency in Boiling Water Reactors under Simulated LOCA Conditions (BWR-FLECHT Final Report)", GEAP-13197, 1971.
2. J.P. Waring, E.R. Rosal and L.E. Hochreiter, "PWR-FLECHT-SET Phase Bl Data Report", ERDA-Report, WCAP-8431, 1974.
3. Y. Lee et al., "A Study of the Process of Rewetting of Hot Surfaces by Flooding", Dept. of Mech. Eng., Univ. of Ottawa, June 1979.
4. A Yamanouchi, "Effect of Core Spray Cooling in Transient State After Loss of Coolant Accident", *J.Nucl. Sci. Tech.*, **5**, 547-558, 1968.
5. R.B. Duffey and D.T.C. Porthouse, "The Physics of Rewetting in Water Reactor Emergency Core Cooling", *Nuc. Eng. Des.*, **25**, 379, 1973.
6. D. Hein, W. Köhler and K. Riedle, "Analysis of Mono-Tube and 340 Rod-Bundle Experiments with a Rewetting Model", Harwell, England, June 1974.
7. K.H. Sun, G.E. Dix, and C.L. Tien, "Cooling of a Very Hot Vertical Surface by a Falling Liquid Film", Trans. ASME, Ser. C, *J.Heat Transfer*, **96**, 126-131, 1974.
8. G. Yadigaroglu, K.P. Yu, L.A. Arrieta and R. Greif, "Heat Transfer During the Reflooding Phase of the LOCA-State of the Art", EPRI 248-1 Topical Report, 1975.
9. D. Butterworth and R.G. Owen, "The Quenching of Hot Surfaces by Top and Bottom Flooding-A Review", AERE-R 7992, 1975.
10. M.E. Sawan and M.W. Carbon, "A Review of Spray-Cooling and Bottom-Flooding Work for LWR Cores", *Nuc. Eng. Des.*, **31**, 191-207, 1975.
11. M.K. Chung, Y.W. Lee and J.H. Cha, "Experimental Study of Rewetting Phenomena", *J. Korean Nuc. Soc.*, **12**, 9-18, March, 1980.
12. Y. Murao, "Analytical Study of Thermo-Hydrodynamic Behavior of Reflood-Phase During LOCA", *J. Nuc. Sci. Tech.*, **16**(11), 802-817, Nov. 1979.
13. Y. Lee and W.J. Chen, "Rewetting of Very Hot Vertical and Horizontal Channels by Flooding", Proceedings, 6th International Heat Transfer Conference, 5, 95, Torronto, Aug. 9-11, 1978.
14. B.D.G. Piggot and D.T.C. Porthouse, "A Correlation of Rewetting Data", *Nuc. Eng. Des.*, **32**, 171-181, 1975.
15. D.F. Elliot and P.W. Rose, "The Quenching of a Heated Surface by a Film of Water in a Steam Environment at Pressures up to 53 bar", AEEW-M976, Mar. 1973.