REFLOOD EXPERIMENTS IN SINGLE ROD CHANNEL UNDER HIGH-PRESSURE CONDITION

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Reflood Experiments in Single Rod Channel under High-Pressure Condition

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Reflood experiments were performed in the single rod test facility of Japan Atomic Energy Research Institute (JAERI). The objective of testing was to investigate thermal-hydraulic behavior during reflood. The primary parametric variables were the reflooding flow rate, initial surface temperature and linear power.

All the experiments were conducted at 1 MPa. In the experiments, saturated water was injected. The experiments covered reflooding flow rate from 0.01 to 0.18 m/s, initial surface temperature from 677 to 903 K and linear power from 0 to 2.712 kw/m. The axial power profile was uniform.

The test results show that the ratio of quench velocity to reflooding flow rate varied from 0.204 to 0.744. There are the effects of thermal parameters on the ratio of quench velocity to reflooding flow rate.

The results of high reflooding flow rate tests indicate the presence of a significant quantity of entrained liquid in the steam flow. The fluid thermocouple located at 2m from inlet of heated region was quenched at 8.5 sec after beginning of reflood and the ratio of liquid penetration velocity to quench velocity reaches 6.39, when reflooding flow rate is 0.18 m/s.

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* Institute of Atomic Energy (IAE), China.
The quench temperature varies between 633 K (lowest value) and 708 K (highest value). It is limited in a narrow range, approximately in 75 K.

The experiments show the film boiling heat transfer coefficients scatter in a narrow band at the same length \( L_Q \) (length from quench front) except for the data measured at low flow rates and low linear powers.

Keywords: Reflood Experiment, Single Rod, Reflooding Flow Rate, Initial Surface Temperature, Linear Power, Quench Velocity, Liquid Penetration Velocity, Quench Temperature, Film Boiling, Heat Transfer Coefficient
高圧条件下での単一燃料棒チャンネル内の再冠水実験

日本原子力研究所 東海研究所原子炉安全工学部
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(1989年10月9日受理)

日本原子力研究所（原研）の単一燃料棒実験装置において、再冠水実験を行った。実験の目的は、再冠水時の熱水力挙動を調べることである。主要なパラメータ変数は、再冠水速度、初期表面温度及び線出力である。

全ての実験は1MPaで行った。また実験では、飽和水を注入した。実験は、0.01～0.18 m/sの再冠水速度、677K～903Kの初期表面温度及び0～2712 kW/mの線出力をカバーしている。軸方向の出力分布は一様である。

実験では、クエンチ速度と再冠水速度の比が、0.204より0.744まで変化した。また、実験では、熱的パラメータのクエンチ速度と再冠水速度の比への効果が見られた。

高再冠水速度実験の結果は、蒸気発生にかかわりの量の玉トレインメント液体が存在していることを示した。再冠水速度が0.18m/sの時、加熱区間の入口より2mの位置にある流体用熱電対は、再冠水開始8.5秒後にクエンチし、液体浸透速度とクエンチ速度の比は6.39に達した。

クエンチ温度は、633Kより708Kまで変化し、その変化は狭い範囲、約75K以内であった。

また、実験結果は、低再冠水速度及び低線出力で得られたデータを除けば、同じく（クエンチフロントよりの距離）の値に対して、獲氷器熱伝達係数は狭い範囲で変化することを示した。
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Nomenclature

E  Emissivity
$h_c$  Film boiling heat transfer coefficient
$h_r$  Radiative heat transfer coefficient
$L_c$  Collapsed liquid level
$L_d$  Distance from quench front
$H_{fg}$  Latent heat of evaporation
$M$  Ratio of quench velocity to reflooding flow rate
$P$  System pressure
$P_p$  Linear power
$q$  Heat flux
$s$  Ratio of liquid penetration velocity to quench velocity
$t$  Time
$t_{lp}$  Liquid penetration velocity
$t_q$  Quench time
$T_s$  Saturation temperature
$T_{wi}$  Initial surface temperature
$U_{in}$  Reflooding flow rate
$U_q$  Quench velocity
$U_{lp}$  Liquid penetration velocity
$Z_q$  Elevation of quench front
$\Delta T_{sat}$  Superheat of coolant
$\Delta T_{sub}$  Inlet subcooling
$\rho$  Density
$\epsilon$  Stefan-Boltzmann constant
$\lambda$  Thermal conductivity
$\mu$  Dynamic viscosity

Subscripts

g  Gas phase
l  Liquid phase
1. Introduction

Single heat rod reflood heat transfer experiments were performed in the single rod test facility. The test region covered the injection condition of low pressure coolant injection system (LPCI) of pressurized water reactor (PWR) and boiling water reactor (BWR). The experiments were conducted to acquire qualitative and quantitative information regarding single rod reflood. The primary parametric variables were the reflooding flow rate, initial surface temperature and linear power. All the experiments were conducted at 1 MPa. In the experiments, the saturated water was injected, i.e. the subcooling was kept at 0 K during reflood.

The report will begin with a description of the single rod test facility and of the experimental procedures used. Then the experimental results will be discussed. Particularly, in this paper, the following topics will be discussed:

1. The effect of thermal parameters on quench front propagation.
2. The ratio of quench velocity to reflooding flow rate.
3. Relationship between quench front and collapsed liquid level.
4. Relationship between quench front and liquid penetration.
5. Quench temperature.
6. The effect of grid spacer on reflood heat transfer.
7. Film boiling heat transfer during reflood.

2. Experimental Apparatus

A schematic diagram of the test loop is shown in Fig 1. It consists of an annular test section, pressure control system, dummy flow path, magnet valves, steam generator, hot water boiler and condenser. Water in the steam generator and hot water boiler is heated to produce high temperature, high pressure steam and water. Steam flows out from the top.
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of steam generator and saturated water flows out from the bottom of the hot water boiler. The steam and water flows into the dummy flow path and test section, respectively, during reflood. Finally the two-phase fluid is condensed in the condenser and the condensed water is drained.

Figure 2 shows detail of the test section. It is composed of a SUS 304 outer tube of 30 mm O.D. and 22 mm I.D. and an inner heater rod of 12.27 mm O.D. The outer tube can be divided into seven flow pieces. The inner rod is composed of three regions: non-heated entrance region of 1892 mm length, heated test region of 2000 mm length and non-heated outlet region of 317 mm length.

The sheath and the heater element are made of NCF 600 (Inconel 600) and Nichrome-5, respectively. The electric insulator inside the heater element is sintered boron nitrid (BN) and the insulator between the heater element and the sheath is packed BN.

Ten chromel-Alumel (C/A) sheathed thermocouples with a sheath outer diameter of 0.5 mm are equipped in the heated region to measure the heater rod surface temperature. The thermocouple is embedded in the groove of 0.5 mm depth on the sheath outer surface. Axial locations of the thermocouples are shown in Fig. 2. The tip of the thermocouple close to the hot junction is welded to the cladding of the heated rod. The heater rod was swaged after mounting the thermocouples to ensure the tight contact of the thermocouple sheath and the heater rod cladding and to make the heat rod surface smooth.

The heated region of rod is heated indirectly by electricity with the uniform axial power distribution.

The structure of the grid spacer is shown in Fig. 2.

The pressures and temperatures of fluid are measured with pressure
transducers and thermocouples, respectively, at the inlet and outlet of the heated test region. The differential pressure across the heated test region is measured with a differential pressure transducer. The steam and water flow rates are measured upstream of the test section using orifice flow meters. Steam and water temperatures are also measured with thermocouples at the inlets of the flow meters. The pressures are measured with pressure transducers at the inlets of the flow meters.

Power supplied to the heater rod is controlled by a silicon controlled rectifier (SCR) power control system and it is measured by a wattmeter.

3. Test Conditions and Procedure

3.1 Test condition

The experimental conditions are listed in Table 1. The reflood tests were conducted in ranges of reflooding flow rate from 0.01 to 0.18 m/s, initial surface temperature from 677 to 903 K and linear power from 0 to 2.712 kw/m. The tests were preformed changing the above parameters systematically.

All the experiments were conducted under 1 MPa. The inlet subcooling is kept at OK (saturated liquid).

3.2 Test procedure

The experimental procedure is as follow:

(1) The system pressure of the facility was first set at the desired pressure.

(2) Saturated steam generated in the steam generator flowed into the test section to blow off water and to ensure the dry condition of the test section and saturated water flowed through the dummy flow path.
(3) The electric power was supplied to the heated rod.

(4) When the heated rod surface temperature reached the desired temperature, the electric power was changed to the desired value and the saturated water at desired flow rate was injected into the test section by closing magnet valve A, D and opening magnet valve B, C. The saturated steam flowed through the dummy flow path after these valve operations.

Date were recorded on a magnetic tape at the recording speed of 50 Hz or 25 Hz for each channel.

During the test, the system pressure was stabilized at the initial pressure and the supplied power was kept constant.

(5) When all the rod surface temperatures showed the cooled conditions, the power supply and the data recording were turned off, terminating the test.

4. Experimental Results

4.1 Quench front propagation and the ratio of quench velocity to reflooding flow rate

Experimental results are presented here for the effects of reflooding flow rate, initial surface temperature and linear power on quench behaviors.

Figure 3 shows the quench front propagation curves for five different reflooding flow rates, with all other conditions kept constant. It can be seen that quench front moves faster when reflooding flow rate is higher. Figure 4 shows the quench front propagation for five linear powers and Figure 5 shows the quench front propagation for four different initial surface temperatures. The test results also indicated the presence of linear power and initial surface temperature effect on quench front propagation. For the high rod power and high initial surface temperature
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cases, the quench front moves slowly.

The reflooding flow rate and the quench velocity are shown in Table 2. The reflooding flow rate ranged from 0.01 m/s to 0.18 m/s and the quench velocity ranged from 0.00496 m/s to 0.0368 m/s. The ratio (M) of quench velocity to reflooding flow rate is also shown in Table 2. The ratio varied from 0.204 to 0.744. On the other hand, it is reported in Refs. [1] and [2] that the ratio of quench velocity to reflooding flow rate varied from 0.32 to 0.47. The relatively narrow range of ratio (M) in these references may be caused by narrow range of reflooding flow rate, initial surface temperature and linear power.

Figures 6 through 8 show the parametric effect on ratio (M) of quench velocity to reflooding flow rate. The effect of linear power on ratio (M) is shown in Fig. 6. The experimental results show that the ratio (M) increases with decreasing the linear power. The effect of reflooding flow rate and initial surface temperature on ratio (M) are very strong. The ratio (M) increases with decreasing the reflooding flow rate and initial surface temperature as shown in Figs. 7 and 8.

4.2 Relative position of collapsed liquid level and quench front

The relationship between collapsed liquid level and quench front position is of interest because a collapsed liquid level greater than the quench level is suggestive of a two-phase mixture level greater than the quench level.

Figures 9 through 11 illustrate the quench and collapsed liquid levels as function of time for three tests. The quench front is observed to be well above the collapsed liquid level for the low reflooding flow rate test (RUN 612, 0.01 m/s). Other test performed at higher reflooding flow rate have some quench points above and some below the collapsed
4.3 Liquid penetration

A liquid penetration front is the maximum heated rod elevation where an exposed fluid thermocouple have been quenched. Figure 12 shows the quench history of fluid thermocouple. The liquid penetration rate is of interest because, to some extent, it characterizes the reflood.

In most of the experiments, the liquid penetration front is moving away from the quench front instead of remaining a fixed distance a head of the quench front.

Figures 13 through 15 show the effect of thermal parameters on ratio \( S \) of liquid penetration velocity to quench velocity. The tendency of increase in ratio \( S \) with linear power and initial surface temperature can be observed. However, the effect of linear power and initial surface temperature are rather small compared with the effect of reflooding flow rate. The effect of reflooding flow rate on ratio \( S \) is very strong. The ratio \( S \) increases with reflooding flow rate. The ratio \( S \) nearly reaches 1 when the reflooding flow rate approaches the lowest value (RUN 612, \( U_{ln} = 0.01 \) m/s). This means that the liquid penetration front remains slightly in front of the quench front and fluid thermocouple quenching occurs at roughly the same time as that of the adjacent heated rod surface quenching. This may indicate low entrainment and a relatively quiescent mixture level. On the other hand, the ratio reaches 6.39 when reflooding flow rate is 0.18 m/s (RUN 652). The penetration velocity is much higher than the quench velocity. The liquid penetration front is far away from the quench front. The fluid thermocouple located at 2 m from inlet of the heated region was quenched at 8.5 sec after beginning of reflood. This means large amount of water is thrown upward and the fluid
thermocouple fluid can be expected to quench much earlier than the
adjacent heated rod surface. The liquid penetration velocity appears to
be an indicator of entrainment. If the penetration velocity was greater
than and distinct from the quench front velocity, significant entrainment
was occurring. If the penetration velocity was roughly equal to the
quench front velocity, significant entrainment was not occurring.

4.4 Quench temperature

Table 3 summarizes the quench temperature measured during reflood
experiments. Quench temperature varies between (lowest value) 633 K and
708 K (highest value). It is limited in the narrow range, approximately
in 75 K.

In Fig. 16, the quench temperature are plotted against the initial
surface temperature. The effect of initial surface temperature on quench
temperature is not observed. Figures 17 and 18 show the effect of
reflooding flow rate and linear power on quench temperature, respectively.
It can be seen that the quench temperature was weakly dependent on linear
power. The test results show the quench temperature increases with
decreasing the reflooding flow rate when the reflooding flow rate is lower
than 0.1 m/s. The quench temperature is nearly the same for reflooding
flow rates of 0.1 m/s and 0.18 m/s.

Some investigator discovered the effect of grid spacer on quench
temperature. In this experiment, the effect of grid spacer on quench
temperature is not seen.

In Fig. 19, the quench temperature are plotted against pressures
together with other investigator's data. Hein et al[6] measured the
minimum film boiling temperature with a internally flooded pipe for a
pressure range of 0.5 to 21 MPa. Koizumi, et al.[7] measured the quench
temperature at Two-phase Flow Test Facility (TPTF). The test section is composed of 25 (5x5) indirected electric heater rods. The test condition ranged 0.5-12 MPa for pressure, 0.3-1.2 m/s for inlet reflooding flow rate and 0 K for inlet subcooling (Saturated liquid). The experimental data are shown in Fig. 19. The present data are very close to these data with tube and rod bundles.

In Fig. 19, some other correlation and test data[2][8]-[11] are shown for comparison. The saturation temperature are also shown for comparison.

4.5 Effect of grid spacer on reflood

Some experimental works[3][4][5] under low pressure have been conducted in order to investigate the effect of grid spacer on reflood heat transfer. The effect of grid spacer on reflood heat transfer have been clarified in these works.

The results of reflood tests performed at the single rod test facility indicated the presence of grid spacer effect on the surface temperature profiles and quench time in some tests. Examples of the temperature profiles are presented in Fig. 20. There is a noticeable lowering of the rod temperature at 1.58 m of elevation. This corresponds to the location of downstream of the grid spacer.

The other grid spacers are installed at 0.685 m and 1.133 m of elevation. Because there are no thermocouples near these grid spacers, the effect of these grid spacers on temperature profiles did not appear.

Quenching behavior is also affected by the grid spacer. Figure 3 through 5 show the effect of grid spacer on quench time downstream of the grid spacer. Quench occurs earlier here in some experiments.

The effect of grid spacer on quench time and rod surface temperature depends on thermal parameters. As shown in Fig. 4, the effect of grid
spacer increases with decreasing the linear power. Significant effect was not observed when the linear power is less than 1.416 kW/m (the initial surface temperature is 860 K and reflooding flow rate is 0.025 m/s).

Figure 3 shows the effect of reflooding flow rate on quench front propagation. The effect of grid spacer increases with reflooding flow rate. No significant effect was observed when the reflood flow rate is less than 0.025 m/s. The effect of initial surface temperature on quench front propagation is shown in Fig. 5. The effect of grid spacer increases with decreasing the initial surface temperature. When initial surface temperature exceeds 860 K, no significant effect appears.

4.6 Film boiling heat transfer coefficient

Figure 21 shows the typical heater rod surface temperature transient measured in the experiment. From this rod surface temperature transient, rod surface heat fluxes were calculated by a heat conduction calculation package of the RELAP5/MOD2. The integral form of the heat conduction equation is

\[
\frac{\partial T}{\partial t} = \iint_{V} \nabla \cdot (\mathbf{K} \nabla T) \, dv - \iiint_{S} \frac{\partial T}{\partial s} \, ds + \iiint_{V} q \, dv \quad \cdots (1)
\]

where \( K \) : thermal conductivity,
\( s \) : surface,
\( S \) : internal heat source,
\( t \) : time,
\( T \) : temperature,
\( \mathbf{\bar{r}} \) : space coordinates
\( \rho \) : volumetric heat capacity

In the calculation of heat fluxes \( q \), the axial heat conduction was
not taken into consideration. Reference [12] indicated the axial heat conduction along the rod can be neglected even at the stage just before the quench time. The effect of axial heat conduction is limited to a short length (about 2 cm) of rod at quench front during the reflood phase.

The boundary condition is the measured rod surface temperature.

The following equations were used for the calculation of film boiling heat transfer coefficient \( h_C \):

\[
q = h_T = h_C + h_r = \frac{q}{T_w - T_s} \quad \text{..... (2)}
\]

\[
h_r = E \varepsilon (T_w^4 - T_{sat}^4) / \Delta T_{sat} \quad \text{..... (3)}
\]

The emissivity of the heater rod surface (Inconel 600) is assumed to be 0.65[13][14].

Figures 22 through 25 show the test results of film boiling heat transfer coefficient. In the figures representative length \( L_Q \) is the distance from the quench front. Figure 22 indicates that except for RUN 612, \( h_C \) are scattered in a narrow band at the same length. The reflooding flow rate is much lower for RUN 612 (\( U_{in} = 0.01 \text{ m/s} \)). Figures 23 through 25 show that \( h_C \) are scattered in the same narrow band for different initial surface temperatures, linear powers and elevations except for RUN 522 and 512 (\( P_p = 0.78 \text{ kw/m} \) and 0 kw/m). The film boiling heat transfer coefficient for low linear powers is much lower than that for high linear powers.

To predict the film boiling heat transfer during reflood phase, many investigations have been conducted.

Bromley[15] developed the theory for vertical heated surface as well as for a horizontal heated cylinder, and it is expressed as
\[ h_C = C \left( \frac{\lambda_g 3 \rho_g (\rho_1 - \rho_g) H_{fg}'}{L \mu_g \Delta T_{sat}} \right)^{1/4} \] 

where the constant \( C \) lies between 0.667 and 0.943.

An empirical reflood heat transfer correlation\(^{[16]}\) was developed by using the PWR-FLECHT data base on upward flooding experiments. For the quasi-steady period, the following correlation was derived:

\[
\begin{align*}
    h_C &= 261.2 \{1-\exp(-9.84 U_{In})\} \{0.714 + 0.0286 \{1-\exp(-0.16843 \rho/ U_{In}^2)\} \} \\
    &+ 215.9 \exp(-5.9 U_{In}) \exp(-3.9371 L_Q) 
\end{align*}
\] 

\[ \cdots (5) \]

Sudo\(^{[17]}\) developed an empirical correlation for the heat transfer coefficient of the saturated and subcooled film boiling regimes under simulated reflood condition. The correlation is

\[
h_C = h_{sat} \left(1 + 0.0025 \Delta T_{sub}\right) + 3/4 hr
\]

\[ \cdots (6) \]

where

\[
\begin{align*}
    h_{sat} &= 0.94 \left[ \lambda_g 3 \rho_g (\rho_1 - \rho_g) H_{fg}' / L \mu_g \Delta T_{sat} \right]^{1/4} \\
    h_r &= E \varepsilon (T_w^4 - T_{sat}^4) / \Delta T_{sat} \\
    H_{fg}' &= H_{fg} \left[1 + 0.4 C_p \Delta T_{sat} / H_{fg}\right]^2 
\end{align*}
\]

The correlation for saturated film boiling is similar to Ellion's correlation except for factor 0.94 and the use of \( H_{fg}' \).

The experimental data are compared with these correlations in Figs. 26 and 27. In the Figures, beside Sudo's correlation and yeh's correlation, Modified Bromley correlation is used for comparison (factor : 0.62).

Modified Bromley correlation and yeh's correlation underestimate the heat transfer coefficient over the region of the present experimental conditions except for low reflood flow rate and low linear power.

Sudo's correlation predicts the experimental results of single rod
experiments well for the representative length $L_Q$ from 2.5 to 40 cm. However, its predictions are higher than results at the low reflooding flow rate and low liner power. In the experiments, quality at quench front ranges from 0 to 0.324.

Figure 28 shows the comparison of calculated heat transfer coefficients (using sudo's correlation) with experimental data (except for RUN 612, 522, 512). The agreement between the calculation and the data is approximately within a range of ± 25%.

5. Conclusions

Reflood experiments were performed in an annular flow channel with an uniformly heated rod under test conditions of the reflooding flow rate from 0.01 to 0.18 m/s, initial surface temperature from 677 to 903 K and linear power from 0 to 2.712 kW/m. From the experimental results and discussions, it is concluded as follows:

(1) In reflood tests, the ratio of quench velocity to reflood flow rate varied from 0.204 to 0.744. The ratio depends on thermal parameters, i.e. the reflooding flow rate, initial surface temperature and linear power.

(2) The effect of reflooding flow rate, initial surface temperature and linear power on the ratio ($S$) of liquid penetration velocity to quench velocity was clarified. The ratio ($S$) reaches nearly 1 when reflood flow rate becomes low. In a high reflood flow rate, the penetration front is far away from quench front. This indicates the existence of significant liquid entrainment in a high reflood flow rate.

(3) Quench temperatures varied between 633 K (lowest) and 708 K
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Figure 28 shows the comparison of calculated heat transfer coefficients (using sudo's correlation) with experimental data (except for RUN 612, 522, 512). The agreement between the calculation and the data is approximately within a range of ± 25%.

5. Conclusions

Reflow experiments were performed in an annular flow channel with an uniformly heated rod under test conditions of the reflooding flow rate from 0.01 to 0.18 m/s, initial surface temperature from 677 to 903 K and linear power from 0 to 2.712 kw/m. From the experimental results and discussions, it is concluded as follows:

1. In reflood tests, the ratio of quench velocity to reflood flow rate varied from 0.204 to 0.744. The ratio depends on thermal parameters, i.e. the reflooding flow rate, initial surface temperature and linear power.

2. The effect of reflooding flow rate, initial surface temperature and linear power on the ratio ($S$) of liquid penetration velocity to quench velocity was clarified. The ratio ($S$) reaches nearly 1 when reflood flow rate becomes low. In a high reflood flow rate, the penetration front is far away from quench front. This indicates the existence of significant liquid entrainment in a high reflood flow rate.

3. Quench temperatures varied between 633 K (lowest) and 708 K
(highest). It is limited in a narrow range, approximately in 75 K.

(4) The results of reflood tests performed in this facility indicated the presence of grid spacer effect on surface temperature profiles and quench times. There was a noticeable the rod temperature and an earlier occurrence of quench downstream of the grid spacer in some tests.

(5) The film boiling heat transfer coefficients scatter in a narrow band at the same length LQ. Sudo's correlation predicts the experimental results well for the representative length LQ from 2.5 to 40 cm and quality at quench front from 0 to 0.324 except for the data measured at low flow rates and low linear powers.

Acknowledgments

The authors wish to express their sincere thanks to Mr. H. Murata of the Japan Atomic Energy Research Institute and Mr. H. Yamada and other members of Nuclear Engineering Co. to conduct the experiments. They are also indebted Mr. E. Umeki of ISL Co. for data processing, Mr. Y. Mimura of ISL Co. for assisting RELAP5 calculation and Miss M. Kikuchi of Nihon Computer Bureau for typing the manuscript.
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5) The film boiling heat transfer coefficients scatter in a narrow band at the same length LQ. Sudo's correlation predicts the experimental results well for the representative length LQ from 2.5 to 40 cm and quality at quench front from 0 to 0.324 except for the data measured at low flow rates and low linear powers.

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References

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(14) Touloukain, Y. S., et al.: "Thermophysical properties of Matter,”
     Vol 7, Pg72 (1970)
Table 1  Experimental conditions

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Table 2  Ratio of quench velocity to reflooding flow rate

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Table 3 Quench temperature and quench time

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Fig. 2  Heater rod used in present experiment
Fig. 3 Quench front propagation

Fig. 4 Quench front propagation
Fig. 5 Quench front propagation

Fig. 6 The ratio of quench velocity to reflooding flow rate
Fig. 7  The ratio of quench velocity to reflooding flow rate

Fig. 8  The ratio of quench velocity to reflooding flow rate
Fig. 9  Quench front and collapsed liquid level vs time

Fig. 10  Quench front and collapsed liquid level vs time
Fig. 11 Quench front and collapsed liquid level vs time

Fig. 12 Quench history of fluid thermocouple
Fig. 13 Ratio of average liquid penetration velocity to average quench velocity

Fig. 14 Ratio of average liquid penetration velocity to average quench velocity
$P_p = 1.416 \text{ kW/m}$
$P = 1 \text{ MPa}$
$U_m = 0.025 \text{ m/s}$

**Fig. 15** Ratio of average liquid penetration velocity to average quench velocity

**Fig. 16** Effect of initial temperature on quench temperature
Fig. 17  Effect of reflooding flow rate on quench temperature

Fig. 18  Effect of linear power on quench temperature
Fig. 19 Quench temperature

Fig. 20 Temperature profile along axial position
Fig. 21  Typical heater rod surface temperature transient

Fig. 22  Effect of reflooding flow rate on film boiling heat transfer coefficient
Fig. 23  Film boiling heat transfer coefficient under different initial surface temperature

Fig. 24  Effect of linear power on film boiling heat transfer coefficient
**Fig. 25** Effect of elevation on film boiling heat transfer coefficient

**Fig. 26** Comparison of calculated and measured heat transfer coefficients
RUN 633
\( P = 1 \text{ MPa} \)
\( P_p = 1.416 \text{ kW/m} \)
\( U_{in} = 0.05 \text{ m/s} \)
\( T_{wi} = 860 \text{ K} \)
No 8 (Z = 1.42 m)

Fig. 27 Comparison of calculated and measured heat transfer coefficients

Fig. 28 Comparison of calculated and measured heat transfer coefficients