

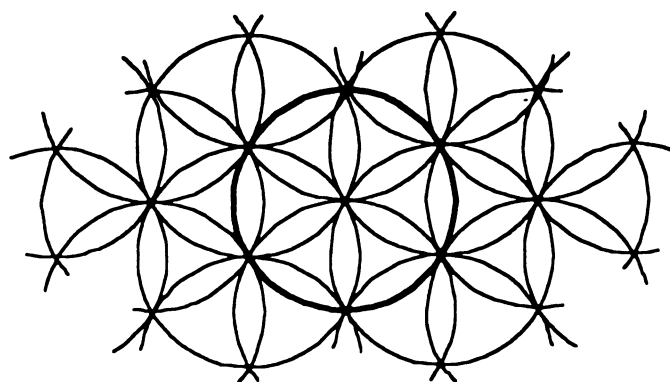
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PROCEEDINGS

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EXPERIMENTAL INVESTIGATION OF THE REWETTING PROCESS AT LOW STEAM PRESSURES

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ABSTRACT

The rewetting of the overheated water cooled nuclear reactor fuel rods after a Loss-of-Coolant-Accident, which is defined as the re-establishment of a water film on the hot rod surfaces, is an important process for the safety of nuclear reactors. Several water experiments have been carried out to investigate the rewetting phenomena and to predict the liquid film behaviour either at atmospheric conditions or in a steam environment. Yet, there seems to be a scarcity of experimental data for the very important low pressure range from 2 to 7 bar with parameters the liquid film flowrate and the subcooling. An experimental facility to simulate two-phase low-pressure water flow phenomena has been designed, constructed and employed to investigate the rewetting process of hot surfaces in a water-steam environment at pressures in the above range, as well as at atmospheric conditions; the facility is on-line interfaced to computers which control its operation and undertake all the data acquisition tasks. The present paper describes the experimental work aimed at studying the wet front propagation along a stainless steel fuel rod in a top-flooding saturated water-steam environment in the pressure range 1 - 7 bar, under various initial wall temperatures up to 550 °C and at a liquid flowrate of 1Lmin⁻¹. Following the experimental results a correlation has been derived to predict the rewetting rate as a function of pressure and initial wall temperature. This correlation agrees well with formerly proposed correlations at higher pressures, thus permitting to extend their validity down to the pressure of 1 bar. Furthermore, a numerical method is introduced to experimentally evaluate the wet front position along the rod.

Introduction.

The rewetting process of overheated surfaces by the advancing liquid film can be considered as a local phenomenon closely related to the Leidenfrost phenomenon. The "rewetting liquid front" -also known as "wet front"- advances into a high temperature region by cooling the surface right in front of it, via axial heat conduction to the wet wall. The length of the front is typically very short. Since the rewetting process is of fundamental importance for the rewetting of overheated fuel elements by the Emergency Core Cooling System (ECCS) of water cooled nuclear reactors, several experiments have been carried out to simulate the rewetting phenomena and to predict the liquid film advancement at atmospheric conditions or in a steam environment. The purpose of this study is to present (1) an especially designed and built facility for the experimental investigation of the rewetting process, (2) experimental results on the wet front propagation along a stainless steel fuel rod at low steam pressures (2-7 bar) and (3) a new experimental-numerical method for the evaluation of the wet front position along the rod.

Experimental Facility.

The test facility (Fig. 1) is a two-phase flow, two-loop experimental rig which was designed

and built in a similar way as that of Simopoulos (1979), which supplies the test section with a continuous flow of liquid water and steam. A heating tank fitted with electric immersion heaters (36 kW), is used as a pressurizer and steam generator. Steam flows from the top of this tank to the test section, while liquid water at saturation temperature is discharged from the bottom of the tank to the test section. The liquid leaving the test section is accumulated in a holding tank along with the steam condensate. The flow to and from the test section can be cut off instantaneously by solenoid valves. A test section by-pass is employed to maintain the facility stability in between experiments. The test section itself consists primarily of a glass tube (25.4 mm i.d.), which encloses a concentric indirectly heated rod. The heated rod is a 1m long tube made of stainless steel filled with magnesia powder, which accommodates a 4.5 kW heater tape.

Twelve iron-constantan thermocouples are embedded inside the stainless steel sheath of the rod, thus ensuring an accurate indication of the wall temperature at different positions along the length of the rod. The liquid flowrate to the test section is measured by a magnetic flowmeter. The pressures around the loop are measured by pressure transducers, while temperatures are measured by chromel-alumel thermocouples. Every measuring device and transducer of the facility is on-line interfaced to computers which control its operation and undertake all the data acquisition tasks.

In-house developed software performs extremely fast and reliable data acquisition from all 50 transducers of the facility at a rate of up to a 100 samples/sec. Real-time calculations of the physical magnitudes around the loop are performed using appropriate correlations for thermophysical properties.

Evaluation of the wet front position.

The sputtering wet front region is characterized by violent transition nucleate-boiling. The length of this region is typically very short and it is reported to be in the order of ten times the wall thickness (Duffey, 1973) or between 1 - 30 mm (Butterworth, 1975). The heat transfer mechanisms in this sputtering region play a dominant role in the cooling process and the localised high cooling rate, which is the result of the transition boiling process, characterises the steep temperature gradient of the wet front (Fig. 2). Convective flow characterises the region well behind the wet front, where a continuous liquid film flows, while ahead of it heat is removed by steam convection, by the dispersed liquid droplets generated at the sputtering region, and by radiation. When the liquid film progresses downward on the vertical hot rod surface, the rod is shock-like cooled down from its initial wall temperature T_w and the surface begins to wet. After the wet front has propagated away from the rewetted surface, the wall temperature gradually continues to decrease down to the saturation temperature T_s with an almost zero gradient. Fig. 2 presents the time history of a thermocouple station inside the wall of a rod, during a rewetting experiment; furthermore, the first and second derivative of the temperature with time, real-time calculated, are also given. It is apparent that there exists an instant at which the rewetting of the rod at a thermocouple station begins and another one at which it ends. At these two instants, the second derivative of the temperature with time obtains its minimum and maximum values respectively. It is between the above mentioned instants, that the wet front passes over the relevant thermocouple station. A numerical method, using real-time temperature data is introduced for the evaluation of the time at which every thermocouple station along the rod is quenched. It should be added that the lack of a fast data acquisition system has not allowed, so far, the proper experimental follow-up of these two gradient transients.

Experimental results.

To our best knowledge, only a few investigators have reported experimental data for the low pressure range between 2 and 7 bar with parameters the liquid film flowrate and the subcooling (Elliot, 1971; Yu, 1977). Furthermore, Hiniš (1994) reports that, experiments both at atmospheric conditions and in a steam environment on the same experimental facility were not communicated. During the experiments presented herein, the test facility, was used to simulate two phase low-pressure water flow phenomena so as to investigate the rewetting process of a hot rod in a top-flooding water-steam environment at pressures in the range 2 - 7 bar (1 bar step), as well as at atmospheric conditions. The initial wall temperatures experimented range between 200 and 550°C (5°C step), while the liquid flowrate was kept constant to 1 Lmin⁻¹.

The initial wall temperature of the rod (T_w) is estimated as the average temperature over all the signals from the iron-constantan thermocouples just prior to the rewetting time at the positions of each one. The inverse rewetting rate u^{-1} is calculated, under steady-state assumption, as the time needed to rewet between the two rod thermocouple stations downstream the inlet to the test section and upstream the outlet, divided by the distance between them (0.7112 m). Following these rather simple calculations the results, at a particular pressure level, fit to a linear model of the form (Fig. 3):

$$u^{-1} = AT_w - B$$

that is valid for inverse rewetting rates greater than the background rewetting rate value of 10 s/m, below which the rod is quenched independently of T_w .

The wet front temperature T_o defined at the $u^{-1} = 0$ s/m level, is calculated by extrapolating these linear correlation models.

The statistical analysis of the fitted results at seven pressures (1 - 7 bar), using the confidence interval ellipses method (Konstantaropoulou, 1991), showed that there exists a pressure effect on the rewetting rate in the range of pressures investigated. However, it has not been possible to express a pressure dependent regression model valid over the whole range of the pressures investigated, inasmuch as the atmospheric conditions data ($P = 1$ bar) could not be fitted together with the steam pressure data. Thus, the atmospheric conditions ($P = 1$ bar) rewetting correlation takes the form:

$$u^{-1} = -188.0 + 0.788T_w \quad (\text{rms error: 42\%})$$

while the steam pressure correlation ($P = 2-7$ bar) is evaluated as:

$$u^{-1} = 0.4P^{-0.22}(T_w - T_o) \quad (\text{rms error: 8\%})$$

It is apparent that the above empirical modelling cannot describe the physical mechanisms controlling rewetting down to atmospheric conditions. It has been possible to extend a physical dimensionless rewetting correlation applicable for a variety of fluids and rod materials introduced by Simopoulos (1981) :

$$\psi_{rew} = C_4(1/T^*)(\rho_v/\rho_l)^{C_2}$$

using additional data from the present atmospheric and steam environment experiments (Fig. 4) with the following results: $C_4 = 2.1 \pm 0.18$, $C_2 = 0.59 \pm 0.02$ (*RMS* error = 13% corr. coeff. = 0.99)

Conclusions.

(1) The experiments have shown that the experimental facility designed and built is suitable for studying two-phase flow phenomena.

(2) It was clearly established, that, for the pressures investigated, there is a strong dependence of the rewetting rate upon pressure and initial wall temperature, expressed by a strong correlation, within the pressure range 2 - 7 bar, that is in good agreement with a similar one proposed by Elliott (1971).

(3) The data collected are well fitted by the rewetting dimensionless correlation proposed by Simopoulos (1981) and extend its validity down to atmospheric conditions.

(4) It is feasible to calculate the wet front position along the rod, by an appropriate numerical method using real-time experimental data.

Nomenclature

g	: acceleration of gravity (m/s^2)
H_{fg}	: heat of evaporation (J/kg)
P	: pressure (bar).
Pr	: Prandtl number ($c_p \mu / k$).
T_o	: wet front temperature ($^{\circ}\text{C}$)
T_s	: saturation temperature ($^{\circ}\text{C}$)
T_w	: wall temperature ($^{\circ}\text{C}$)
T^*	: dimensionless temperature $[(T_o - T_s)/(T_w - T_o)]$
u	: rewetting rate (m/s)
v^*	: dimensionless inverse rewetting rate $[u^{-1}(\sigma g / \rho_l)^{1/4}]$

Greek Symbols

ψ_{rew}	: $(v^* Pr_l^{-0.3})(H_{fg} \rho_v) / [\rho_w c_w (T_o - T_s)]$
ρ	: density (kg/m^3)
σ	: surface tension (N/m)

Subscripts

l	: liquid
v	: vapour
w	: wall

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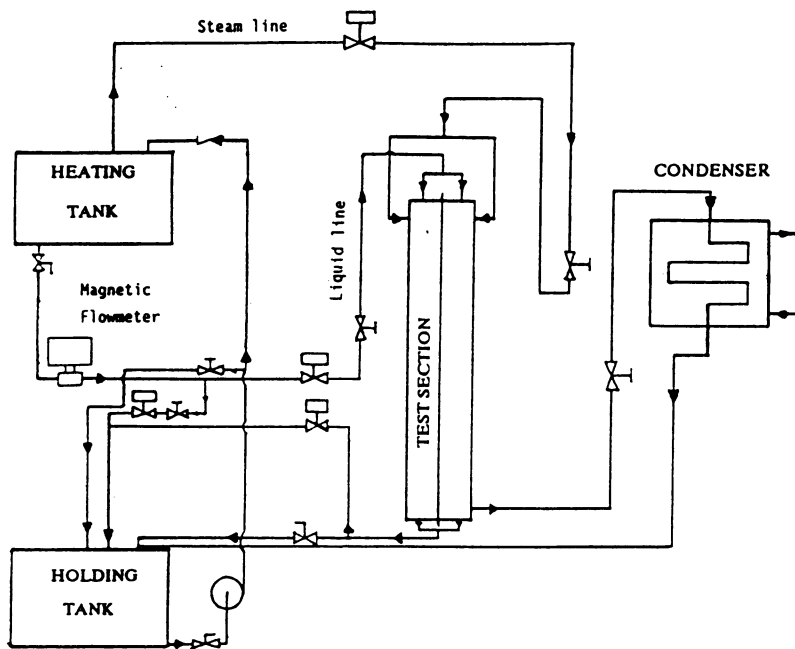


Figure 1 : Experimental Facility

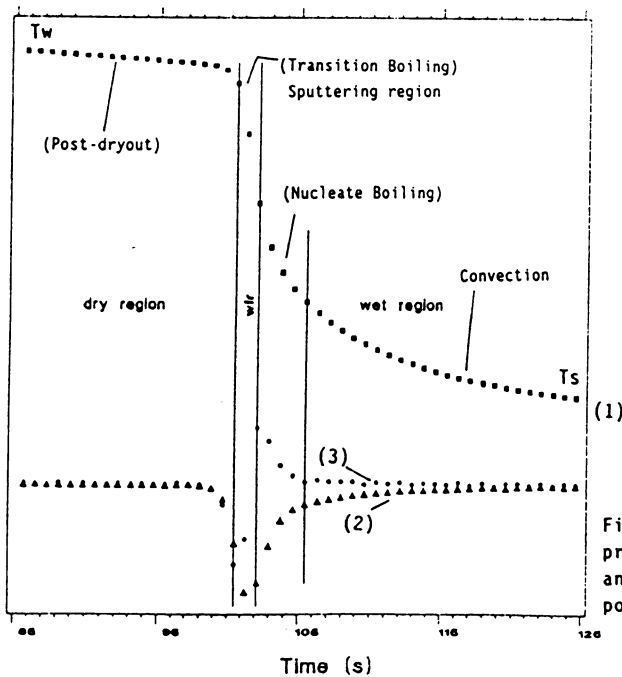


Figure 2: Time temperature profile (1) and its 1st (2) and 2nd (3) derivative at position T/C 5 of the wall.

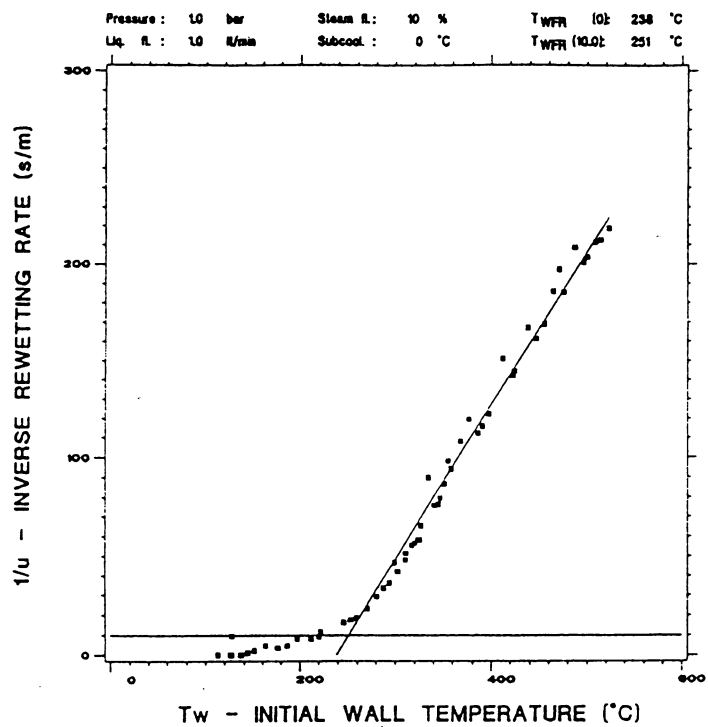


Figure 3: Results of rewetting experiment at atmospheric conditions ($P=1$ bar), liquid flowrate 1Lpm, subcooling 0°C ($T_s=238$ °C)

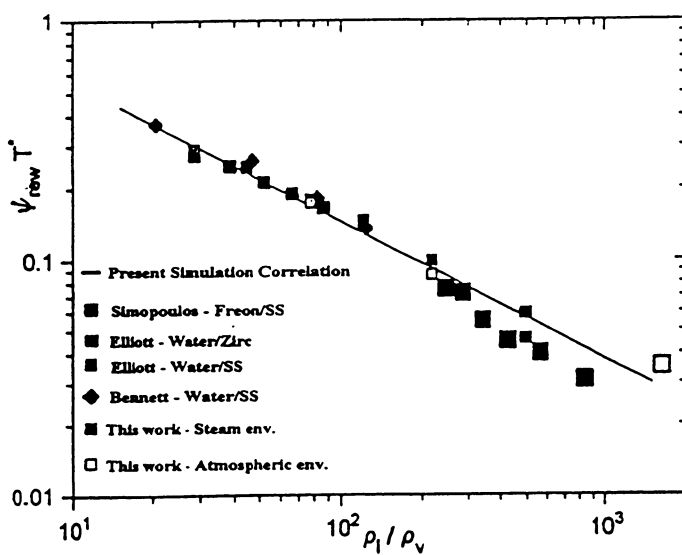


Figure 4 : Dimensionless Rewetting Correlation