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INVESTIGATION OF THE LIQUID FLOWRATE EFFECT ON THE REWETTING RATE

A.P.Konstantaropoulou and S.E.Simopoulos

Nuclear Engineering Section
Mechanical Engineering Department
National Technical University of Athens, Greece

ABSTRACT

Following a Loss-of-Coolant Accident (LOCA) in a water cooled nuclear reactor, process of fundamental importance is the rewetting of the overheated fuel elements by an Emergency Core Cooling System (ECCS). It is well accepted that the rate of advance of the wet front depends upon several parameters, the most important being the initial temperature of the overheated fuel elements cladding, the system pressure, the heat transfer coefficient at the wet front, and the properties of the cladding. The effect of secondary parameters, such as the quenching liquid inlet subcooling and flowrate, and the precursory cooling ahead of the wet front due to the droplet-vapor mixture, are still under investigation. The present work is a detailed statistical analysis of available experimental data. It uses the method of confidence interval ellipses, to investigate the liquid flowrate effect on the rewetting rate. The results of this analysis show that the rewetting rate increases with the liquid flowrate only when the wet front advances in an open air environment at atmospheric pressure, while it remains unaffected in a vapor environment at relatively high pressures.

NOMENCLATURE

Bi	Biot number, $h\delta/k$
h	heat trasfer coefficient (W/m^2K)
P	pressure (bar)
u	rewetting rate (m/s)
T_0	wet front temperature (K)
T_s	saturation temperature (K)
T_w	wall temperature (K)
T^*	dimensionless temperature, equation (2)
W	inlet liquid flowrate (g/s)
ΔT_{sub}	inlet liquid subcooling (K)

1. INTRODUCTION

A process of fundamental importance following a Loss-of-Coolant Accident (LOCA) in water cooled nuclear reactors is the *rewetting* of the overheated fuel elements by an Emergency Core Cooling System (ECCS). Several types of ECCS have been designed and used to date. They all have two common characteristics: liquid is either sprayed into the fuel elements from the top or/and the reactor is flooded with liquid from the bottom. In either case all the two-phase flow regimes, pre-dry-out, dry-out and post-dry-out appear in the course of the rewetting process.

There is considerable evidence from both theoretical and experimental work which indicates that the process of rewetting of hot surfaces by the advancing liquid film can be considered as a local phenomenon, closely related to the Leidenfrost phenomenon (Semeria [1], Yamanouchi [2], Thompson [3], Sun [4]). The rewetting liquid front or *quench front* advances into a high temperature region by cooling the preceding solid surface via axial heat conduction to the wet wall region. Violent transition nucleate boiling characterizes the region just behind the wet front *sputtering region,* the length of which is typically very short (1-30 mm). The heat transfer mechanisms in the sputtering region play a dominant role in the cooling process, and the localized high cooling rate, which is a result of the transition boiling process, characterizes the shock-like temperature gradient of the wet front. Convective flow characterizes the region well behind the wet front where a continuous liquid film flows. Ahead of the wet front, heat is removed by radiation and by vapor convection, by the dispersed liquid droplets generated at the sputtering region.

Previous studies investigating the rewetting process have been surveyed in detail (Butterworth [6], Elias [7], Sawan [8], Simopoulos [9], Carbajo [10,11], Olek [12] and Gerweck [13]). Several water experiments have been carried out to simulate the rewetting phenomena and to predict the liquid film behaviour. Most of these experiments investigated the water rewetting process either in an open air environment or in a steam environment at low pressures while there is poor evidence from experiments at high pressures. In a very few experiments the water rewetting process has been simulated by other liquids. One experiment [14] has been conducted using liquid nitrogen at atmospheric pressure. Two other experiments used Freon-113, one [9,15,16] in a vapor environment at high pressures, and the other [17,18] at atmospheric pressure.

It is well accepted that the rate of advance of the wet front, the *rewetting rate,* depends upon several parameters, the most important of which are known to be the initial temperature of the overheated wall, the system pressure, the heat transfer coefficient at the wet front, and the physical properties of the wall. The effect of secondary parameters, such as the quenching liquid inlet flowrate and subcooling, the surface conditions of the wall, and also the precursory cooling due to the droplet-vapor mixture ahead of the wet front are still under investigation.

Various 1-D and 2-D heat conduction models have been proposed to describe the rewetting process. All these models provide explicit or implicit relationships between a normalized wet front velocity, a dimensionless wall temperature (which contains the wet front temperature and the saturation temperature) and - in general - three Biot numbers characterizing the heat transfer in the three regions along the wall: the wet region, the sputtering region and the dry region. The prediction of the wet front velocity by analytical models requires knowledge of the wall temperature and - at least - of the surface heat transfer coefficient at the wet front. Furthermore, the heat transfer coefficient at the wet region as well as its axial distribution in the dry region are also required by more elaborate models. Thus, experimental data are still needed for using these analytical models.

Many workers use experimental data to obtain simple correlations for the rewetting velocity and the wet front temperature in the form :

$$u = A\, T^* \tag{1}$$

where T* is the *dimensionless initial wall temperature* :

$$T^* = \frac{T_0 - T_s}{T_w - T_s} \tag{2}$$

A a pressure dependent *rewetting coefficient* into which various effects affecting the phenomenon are lumped, T_0 the wet front temperature, T_w the wall temperature, and T_s the saturation temperature.

More elaborate, semi-empirical correlations explicitly correlate the rewetting rate with physical parameters such as the pressure, the liquid flowrate and the liquid inlet subcooling. However, all correlations are based on simplified physical models and no certain physical meaning can be assigned to parameters extracted from the data. Furthermore, there are parameters, such as the liquid flowrate, the effect of which is not yet well clarified. In this paper, we review the literature on the liquid flowrate effect and, further investigate the effect by means of a detailed statistical analysis of available raw data.

2. A REVIEW ON THE LIQUID FLOWRATE EFFECT

A variety of views is found in the literature concerning the liquid flowrate effect. Chronologically they may be summarized as follows.

Following their historically first atmospheric water rewetting experiment, **Shires et al.** [19], concluded that the rewetting rate depends on the water flowrate. It is worth mentioning that this conclusion is based on experiments at three water flowrates (5, 10 and 20 g/s) with a total of only 10 observations.

After conducting a high pressure (6.9 to 69 bar) rewetting experiment in a steam environment, **Bennett et al.** [20] concluded that there is no significant effect of varying the flowrate. However, most of their tests were carried out at a nominally constant flowrate of ~10g/s, while they performed only three tests at three other flowrates (4, 13 and 18 g/s), i.e., one test at each flowrate level at the pressure of 20.7 bar.

The experiments by **Yamanouchi** [2], conducted at atmospheric pressure and at the flowrate levels of 0.5, 1, 1.7, 6.7 and 16.7 g/s, lead to the conclusion that variations in the flowrate have a relatively small effect, while an increase of about 30 times in flowrate only roughly doubles the rewetting rate. It should be added that experimental data collected at flowrates smaller than 6.7 g/s were very few (less than 4 points at each flowrate level).

Yoshioka and Hasegawa [21] conducted their atmospheric experiments at a wide range of water flowrates (0.5 to 40 g/s) but only at three wall temperatures (300, 400 and 500 °C). They concluded that the liquid flowrate effect on the rewetting rate can be empirically correlated by a relation in the form:

$$u = a\ W^{1.25} \tag{3}$$

where u the rewetting rate, W the inlet liquid flowrate, and a a constant.

This finding is in disagreement with that of Yamanouchi [2] because a 30-fold increase in flowrate results in a 70-fold increase of the rewetting rate!

The experiments by **Elliott and Rose** [22,23] are considered as the most complete set of single rod experiments carried out in a steam environment, covering a range of water flowrates from 7.5 to 30 g/s, for pressures from 3.4 to 53 bar. From the tests, these investigators concluded that the rewetting rate is independent of the cooling water flowrate. Furthermore, they suggested that the water flowrate effect reported by previous investigators [19,21] may have been caused by the presence of atmospheric air.

A comprehensive experimental investigation was undertaken by CEGB [5,24,25,26]. From the results of single rod and pin cluster atmospheric experiments together with available world rewetting data at both atmospheric and steam environment conditions, **Piggott and Porthouse** [26] derived the following correlation for the range of interest in water reactor emergency cooling systems:

$$u = a\ W \tag{4}$$

It is noteworthy that the above correlation fits within a factor of 2 the PWR-FLECHT [27] and BWR-FLECHT [28] data at pressures up to 20 bar and the set of Elliott and Rose [22,23] data at four flowrates (7.5 to 30 g/s), averaged to 18.5 g/s, but fails to fit the data of Bennett et al. [20]. For these reasons Piggott and Porthouse [26], concluded that there is no evidence of a flowrate dependence for pressures above 20 bar.

Thompson [29] suggests that, at atmospheric pressures, the mass flowrate affects precursory cooling rather than the wet-side heat transfer coefficient. Therefore, in the absence of precursory cooling the rewetting rate is independent of cooling water flowrate. It is under this assumption that he presented his correlation, using experimental results at several flowrate levels without including it as a parameter.

Yu et al. [30] consider practically all the available time rewetting data until 1976, a total of some 3750 points, and derive correlations of fairly good validity. Moreover, after conducting tests in a steam environment with pressures of 1 to 14.8 bar they find that for saturated flows there is a significant dependence of wet front velocity on flowrate for low pressures, but that this dependence decreases with increasing pressure to the extent that there is no significant flowrate effect at pressures above 3.4 bar. For subcooled water at the wet front, however, they find a significant dependence at all pressures. These investigators were careful to make a distinction between subcooling of the injected liquid and subcooling at the wet front. The above effects are evident in their correlation:

$$h\cdot(T_0 - T_s) = a(1+b\cdot\Delta T_{sub}\cdot W)^2(c+d\cdot \log P)W^{0.153/P} \tag{5}$$

where a,b,c,d constants, h the heat trasfer coefficient, ΔT_{sub} the inlet liquid subcooling, and P the pressure.

Thus, for saturated flows and Biot numbers Bi>>1, which is typical in water reactor rewetting situations this correlation reduces to :

$$u = a\ W^{0.153/P} \tag{6}$$

Using the data of PWR-FLECHT [27] experiments, **Murao** [31] obtained a correlation to predict the rewetting rate within ±20% accuracy valid for pressures 1 to 4 bar, independent of the water flowrate.

Simopoulos [9] carried out a vapor freon-113 environment rewetting experiment at pressures up to 5.43 bar to simulate the high pressure steam environment rewetting process.

Statistical analysis of the experimental data [15] indicates that there is no evidence of a statistically significant liquid flowrate effect. Furthermore, a simulation analysis which followed [16] gave simulation laws for the water/freon-113 vapor-environment rewetting process, with ±9% accuracy, independent of the liquid flowrate.

By their atmospheric pressure experiments, Dhir et al. [32] confirm the view previously expressed by Duffey and Porthouse [25] that the rewetting rate depends upon the square root of the liquid flowrate.

After experimenting with saturated freon-113 at atmospheric pressure, Ueda et al. [17] were rather hesitant to draw any conclusion about the flowrate effect. It is worth drawing attention to the fact that a very wide range of flowrates (0.004 to 0.044 kg/s) is covered in these tests, as compared with that of the high pressure tests by Simopoulos [15] (0.016 to 0.047 kg/s). The results of an extension of this research are reported by Ueda and Inoue [18]. They consider the inlet subcooling of freon-113 up to 38 K, and find the correlation:

$$u = a(W\,\Delta T_{sub})^{0.4} \tag{7}$$

Abe et al. [33] correlate data from both their low pressure (1.5 to 4 bar) SCTF and FLECHT [27,28] (1 to 6 bar) experiments. Their conclusion is that a coolant flowrate effect does not clearly appear.

In summary, the preceding review suggests that :

- The rewetting rate depends on the liquid flowrate when the quench front advances in an open air environment at atmospheric pressure. This dependence is expressed by a relation in the form :

  $$u = a\cdot W^{b} \tag{8}$$

  where b varies from 0.2 to 2.
- When rewetting in a steam environment at pressures greater than ~3 bar this dependence becomes very weak and may be expressed by a relation in the form :

  $$u = a\cdot W^{b/P} \tag{9}$$

  where b a positive constant.

3. STATISTICAL ANALYSIS FOR THE INVESTIGATION OF THE FLOWRATE EFFECT

It is surprising to note that the conclusions drawn by the researchers reviewed in the preceding review, in most cases were not examined statistically. A characteristic example is the following quotation from a review paper by

Butterworth [6] referring to the results of Elliott et al. [22,23]: "*... a small flowrate dependence may go unnoticed with such a scatter in the data. Further, one can detect a slight flowrate effect since, despite the scatter, the low flowrate points tend to lie higher than high flowrate points ...*". We believe that, when rewetting with saturated liquid, an investigation of the inlet liquid flowrate effect should start with a proper statistical analysis of raw data to definitely state the existence of a dependence between the rewetting rate and the liquid flowrate. After this statistical analysis, one can derive a correlation between these two physical variables.

An appropriate statistical method applicable to this investigation is that of the *confidence interval ellipses* [34]. Based on both theoretical and experimental evidence, it is generally well accepted that the relation between the inverse rewetting rate (u^{-1}) and the initial wall temperature (T_w) is expressed by a linear equation of the form:

$$u^{-1} = a_0 + a_1 \cdot T_w \qquad (10)$$

where it is assumed that all other variables involved are kept constant.

The process of a least squares fitting :

$$[Y] = [X][a]+[e] \qquad (11)$$

where: [Y] : a ($n\times 1$) vector of the values of the dependent variable
[X] : a ($n\times m$) matrix of the values of the m independent variables
[a] : a ($m\times 1$) vector of parameters
[e] : a ($n\times 1$) vector of errors

in order to evaluate the best estimations [α] of the *m* parameters [a] associates them with statistical errors, given by simple formulae, which lead to the estimation of individual confidence intervals for each one of the *m* parameters. However, since the *m* parameters are correlated between them, their errors are also correlated and a 100($1-\alpha$)% joint confidence region for both parameters [a] can be obtained from the equation:

$$([a]-[\alpha])'[X]'[X]([a]-[\alpha]) \le m \cdot s^2 \cdot F(m,n-m,1-\alpha) \qquad (12)$$

where:

s^2 is the regression residual, and
$F(m,n-m,1-\alpha)$ is the ($1-\alpha$) point (upper α- point) of the F-statistical distribution

The inequality above provides the equation of an "elliptically shaped" contour in a space which has as many dimensions as there are parameters in [a].

In the case of a straight line fitting, the joint (1-α) confidence region for the two parameters a_0, a_1 is a long, rather thin, ellipse. The coordinates of the center of the ellipse are the best estimations of a_0, a_1 (α_0 and α_1 respectively). The ellipse encloses values (a_0,a_1) which the data regard as jointly reasonable for the parameters [9]. The individual confidence intervals for a_0 and a_1 separately are appropriate for specifying ranges for each one of the parameters irrespective of the value of the other parameter, while the region bounded by an ellipse is one which may be expected with (1-α) confidence to include jointly reasonable values of both, considered as a whole. Inspection of the relative position of two or more ellipses may lead to important conclusions regarding the associated experimental sets :

a) The 99% confidence interval ellipses do not have any common region (fig.1)

In this case the differences of the values of the relevant rewetting parameters (a_0,a_1) in the experimental sets considered are significant and, therefore, these sets are statistically independent. Consequently, a controlled parameter, at different levels of which these sets might have been collected - such as the flowrate - affects the physical process under investigation.

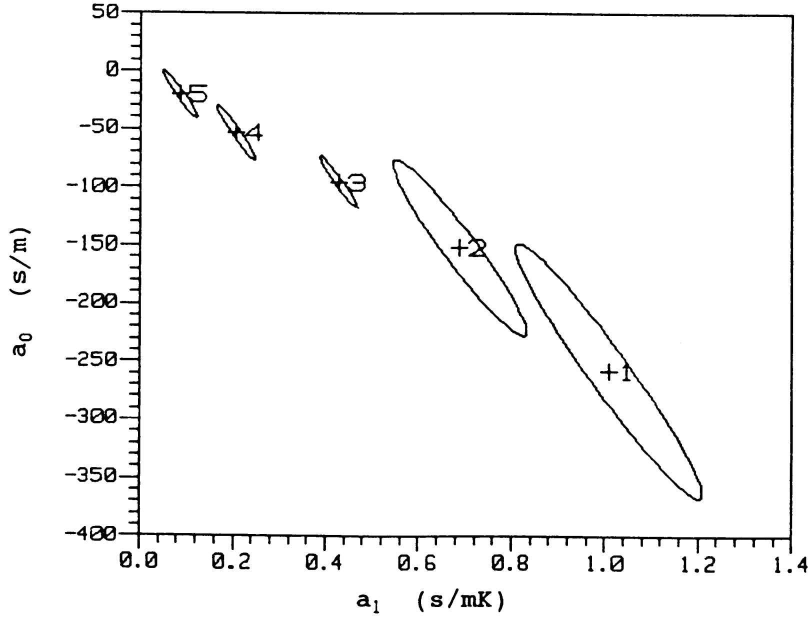

Figure -1 : 99% confidence interval ellipses of the experiments by Duffey [5] at 1 bar with parameter the flowrate (1:0.33, 2:0.92, 3:2.1, 4:4.3, 5:9.5 g/s)

b) The 95% confidence interval ellipses overlap (fig.2)

In this case the differences of the values of the relevant rewetting parameters (a_0, a_1) in the experimental sets considered are not significant and, therefore, these sets do not entail any statistical independence. Consequently, the statistical hypothesis, about the effect of a controlled parameter the value of which changes through the experimental sets examined, has to be rejected at the 5% significance level accepted.

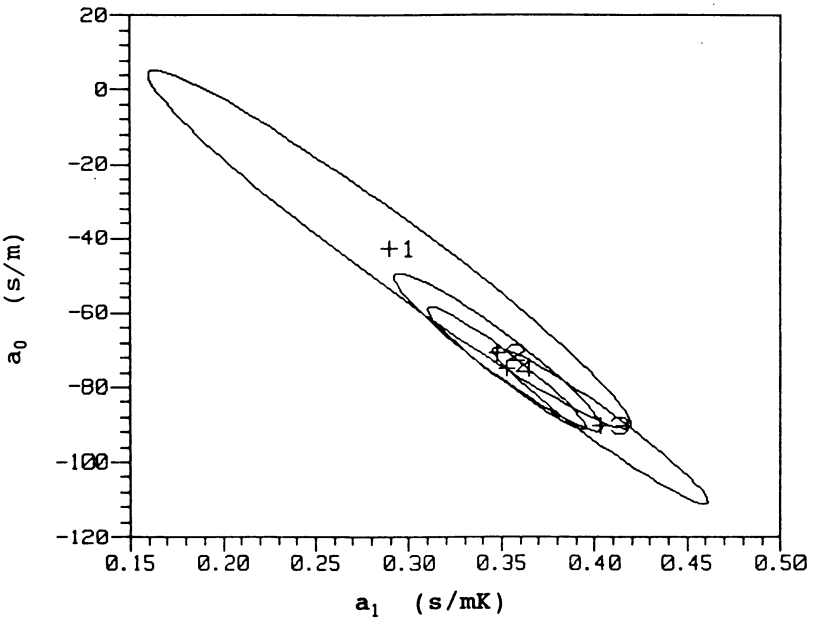

Figure 2 : 95% confidence interval ellipses of the experiments by Elliott [22] at 3.45 bar with parameter the flowrate (1:7.5, 2:15.0, 3:22.5, 4:30.0 g/s)

c) In any other case no conclusion can be drawn out of the experimental data examined, probably due to their excessive scatter and/or the existence of additional uncontrolled parameters in this experiment.

The statistical analysis presented above has been performed to plot the confidence interval ellipses, directly using raw rewetting data $(u_i^{-1}, T_{w,i})$, following an algorithm developed in [9]. For this purpose appropriate computer programs linked with subroutines of the Unix - Starbase library were written to produce graphs, like those already presented, as a characteristic example, in figures 1 and 2 [35].

Table 1 : Experimental data analysed and resulted liquid flowrate effect.

Reference	Fluid	Wall	Rod diameter - Wall thickness (mm)	Pressure (bar)	Flowrate levels (g/s)	99% ellipses overlap	95% ellipses overlap	Flowrate effect
Elliott [22]	Water	St.Steel	15.9 - 1.27	3.43	7.5-15.0-22.5-30.0		Yes	No
Elliott [22]	Water	St.Steel	15.9 - 1.27	7.87	7.5-15.0-22.5-30.0		Yes	No
Elliott [22]	Water	St.Steel	15.9 - 1.27	21.70	7.5-15.0-22.5-30.0		Yes	No
Elliott [22]	Water	St.Steel	15.9 - 1.27	52.80	7.5-15.0-22.5-30.0		Yes	No
Elliott [23]	Water	Zircaloy	15.9 - 1.27	7.87	7.5-15.0-22.5-30.0		Yes	No
Duffey [5]	Water	St.Steel	6.0 - 0.50	1	0.33-0.92-2.1-4.3-9.5	No		Yes
Duffey [5]	Water	St.Steel	12.0 - 0.85	1	0.1-0.5-1.2-6.2-18-27-37	No		Yes
Andreoni [36]	Water	Inconel	10.2 - 1.0	1	11.6-17.4-29.1-41.8	No		Yes
Simopoulos [15]	Freon-113	St.Steel	15.9 - 3.7	1.70	16-26-37-47		Yes	No
Simopoulos [15]	Freon-113	St.Steel	15.9 - 3.7	2.39	16-26-37-47		Yes	No
Simopoulos [15]	Freon-113	St.Steel	15.9 - 3.7	3.08	16-26-37-47		Yes	No
Simopoulos [15]	Freon-113	St.Steel	15.9 - 3.7	3.77	16-26-37-47		Yes	No
Simopoulos [15]	Freon-113	St.Steel	15.9 - 3.7	4.46	16-26-37-47		Yes	No
Simopoulos [15]	Freon-113	St.Steel	15.9 - 3.7	5.15	16-26-37-47		Yes	No
Ueda [17]	Freon-113	St.Steel	16.0 - 0.5	1	4.4-6.3-22.2-44.4		Yes	No
Ueda [17]	Freon-113	St.Steel	16.0 - 1.0	1	4.4-6.3-12.7			
Ueda [17]	Freon-113	St.Steel	16.0 - 2.0	1	4.4-12.7		Yes	No
Ueda [17]	Freon-113	St.Steel	16.0 - 3.0	1	4.4-6.3-12.7-22.2		Yes	No
Ueda [18]	Freon-113	St.Steel	16.0 - 2.0	1	6.4-12.6-22.6	No		Yes

Table 1 summarizes the results of the available raw experimental data analysed. It should be mentioned that the FLECHT [27,28] data have not been considered for the following reasons: (a) These pin bundle experiments used a cosine power distribution. (b) It is difficult to evaluate the *per pin flowrate* and also to account for mass transfer effects between neighbouring pins, in a pin bundle experiment. (c) For secondary reasons well explained elsewhere [25,32]. It is believed that experiments like FLECHT offer the virtues of a full length experiment but, at the same time, present difficulties in understanding physical phenomena and mechanisms. It is probably due to the above reasons that opposite views have been expressed [26,30,31,33] about the flowrate effect in these experiments.

The steam environment pressure data (1 to 14 bar) reported by Yu et al. [30] are also not considered since they are not available in the open literature.

4. CONCLUSIONS

The results of the confidence interval ellipses analysis (Table 1) led us to the following conclusions:

a) When rewetting in a vapor environment at relatively high pressures (either greater than 3.43 bar in a steam environment, or greater than 1.7 bar in a vapor freon-113 environment), the rewetting rate does not significantly depend upon the inlet liquid flowrate. The argument of previous investigators that there exists a small flowrate dependence in the experiments by Elliott and Rose [22,23] is not at all justified by the present statistical analysis.

b) The rewetting rate depends on the liquid flowrate when the quench front advances in an open air environment at atmospheric pressure. The fact that this conclusion is not justified by the results of Ueda et al. [17] - which contradict the results of a further experiment of the same investigators [18] - is not understood and may be due to some uncontrolled parameter of the experiment.

When rewetting with saturated liquids, we believe that the liquid flowrate effect is mainly due to precursory cooling. Precursory cooling has been shown to be able to greatly increase the rewetting velocity, in particular for cases of high flowrates [37,38,39]. On the other hand, precursory cooling seems to be more effective when rewetting in an open air environment, where sputtered droplets are not easily carried away by the co-current vapor flow.

We also believe that there is a lack of systematic, statistically reliable rewetting data in the pressure range from 1 to 6 bar, for flowrates between 1 and 100 g/s. Moreover, we suggest that experiments in both an open air and a steam environment must be carried out using the same experimental facility - even the same test section - in order to keep as constant as possible the values of other parameters which might affect this very sensitive phenomenon. For this purpose, we intend to conduct experiments at the recently commissioned NTUA-Nuclear Engineering Section two-phase flow, two-loop, computer-controlled experimental facility, which has been designed and built in a way to satisfy the requirements of a well controlled rewetting experiment.

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