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The Farahat sodium natural convection film boiling experiment revisited

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ABSTRACT

With the renewal of interest for sodium-cooled fast reactors, looking at what is known from the past, it appears – in the frame of severe accident studies in general and FCI in particular, that very few is known about sodium film boiling around hot fuel droplets which is a condition allowing premixing. The past Farahat experiment (Reynolds et al., 1976), performed in 1971, in which hot solid spheres were transferred into sodium has been revisited. Looking in the detailed results, it appears that a phenomena has been ignored, i.e. the existence of two film boiling regimes as observed in similar experiments with water (Honda et al., 1995; Bradfield, 1966). These two film boiling regimes have been analyzed since the transition between these regimes could lead to the onset of spontaneous explosions if the melt is still liquid at this transition. A simple model has been built for the estimation of this transition point. As this model is able to describe the transition observed in Sn-H_2O experiments (Sher, 2012), it has been used for UO_2-Na systems.

1. Introduction

With the renewal of interest for sodium-cooled fast reactors (Generation IV), it is interesting to look at what knowledge is missing or has to be improved in that area. In the frame of severe accident studies, one point of importance is the consequences of large scale Fuel Coolant Interactions (FCI) which may occur after core melting. From the 1990's, it is recognized that large scale FCIs are possible with sodium as coolant [1]. The main difference with FCIs with water lies in the difficulty to mix large masses of fuel with sodium due to the difficulty to get very stable film boiling with subcooled sodium. In fact, in most of the tests, multiple interactions were observed while fuel was introduced into the coolant. However, with sodium close to saturation, the FCI behavior looks very similar with both coolants. This can occur with sodium initially close to saturation during the accident sequence or sodium being progressively heated during successive FCIs [1].

It is then interesting to study the film boiling stability of heated spheres plunged into sodium. In fact, in similar experiments with water, see [2] for example, under certain circumstances, during quenching in the film boiling regime, there is first a low cooling rate regime (see for example the red[2] curve in Fig. 1: for point D, the superheat is greater than 750 °C and the cooling rate is about 2.6 MW/m^2), followed by a rapid increase towards a large heat flux (~8 MW/m^2 after point E on the red curve) then followed by a small decrease of the flux (point E to point F) as in usual boiling curved.

It was reported that such a behavior was favored by high superheats, low subcoolings, small diameters and low relative velocities. In [3], it was added that it was also favored by high pressures.

In [3], it was also proposed that this type of behavior, i.e. transition from a low heat flux boiling regime towards a higher heat flux film boiling regime, was associated with the appearance of instabilities at the vapor liquid interface during quenching leading to transient liquid-solid contacts and/or small droplet entrainment towards the rear region, both mechanisms increasing heat transfer. In fact, these local and intermittent liquid-solid contacts have been "measured" in Refs. [4,5]. Such liquid-solid contacts during film boiling were originally reported by Bradfield [6].

An illustration of these behaviors is given in the following Fig. 2.

More recently, these two regimes have also been observed in some experiments in which hot (600 °C) solid spheres are dipped into water [7]. From the temperature evolution of the spheres, the heat flux curves are deduced. Results for two diameter sizes (16 and 32 mm) show very different behaviors as shown in Fig. 3.

In Fig. 3a, for the 16 mm diameter sphere, are found classical boiling curves with an abrupt transition towards transition boiling at the usual minimum film boiling temperature. While for the 32 mm diameter sphere (Fig. 3b), it is observed that above a certain subcooling, film collapsing noise and higher heat transfer rates are

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[2] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.

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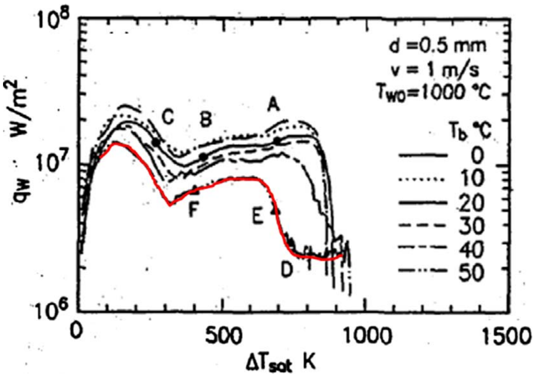

Fig. 1. Boiling curves according to coolant temperature in Honda et al. [2].

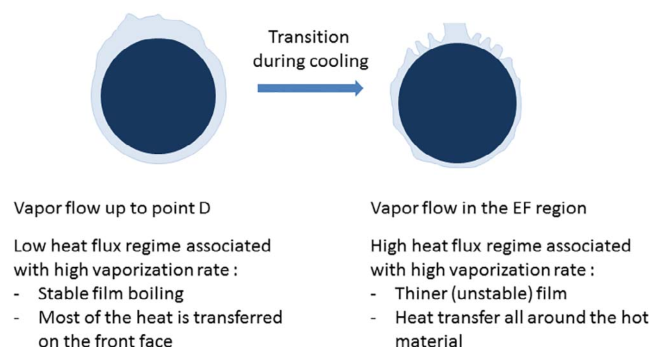

Fig. 2. Scheme of the two film boiling regimes during cooling. (Points D, E, F refers to the points on Honda cooling curves reported Fig. 1).

observed after some period of low heat fluxes.

This explanation is also supported by the single droplet FCI experiments of Reynolds [8] exploring the Temperature Interaction Zone (TIZ), the domain in the plane "initial droplet temperature - initial coolant temperature" where spontaneous (i.e. without trigger) interactions were observed. Such a TIZ is reported in Fig. 4.

For Reynolds et al., the diagonal boundary of the measured TIZ is associated to the transition between a "thick film regime" and a "thin film regime" during which some coolant comes into contact with the liquid fuel, contacts leading to the explosion.

If we apply these ideas to FCI studies for nuclear reactors, it appears that a thermal destabilization of the vapor film would appear at a fuel temperature such that the fuel has been solidified for a long time for water-cooled reactors. However, it appears to be desirable to study this

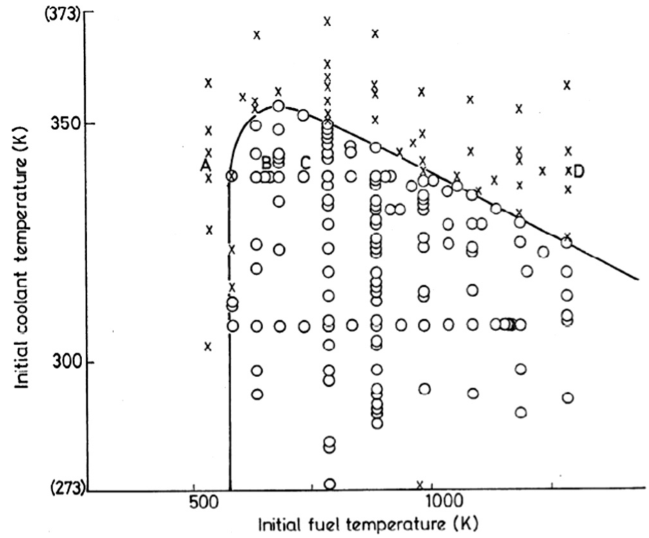

Fig. 4. Fuel-coolant interaction zone for 1.2×10^{-2} kg of tin dropped into water (0 indicates interaction, X indicates no interaction) (Fig. 5 from [8]).

for sodium-cooled nuclear reactors. It is the reason why we have revisited the only sodium film boiling experiment around a sphere i.e. the Farahat one [9], performed in 1971.

2. The Farahat natural convection film boiling experiment in sodium [9]

2.1. Experimental set-up

In this experiment, a tantalum sphere (diameter D_s from 12.7 mm to 25.4 mm) is heated in an induction oven up to 2334 K and plunged into a subcooled sodium pool (subcooling from 4.1 K to 29.1 K). A thermocouple located close to the bottom surface of the sphere allows, through conduction calculations, the evaluation of the heat flux lost by the sphere (see Fig. 5).

Unfortunately, the presence of the support rod with a diameter d_{rod}, not negligible according to the sphere diameter, disturbs the flow at the rear part of the sphere, increasing heat transfer. To take this into account, it is possible to use the correction proposed by Hässler [10], based on natural convection film boiling experiments in water around a heated sphere, who proposed a corrected Nusselt number according to:

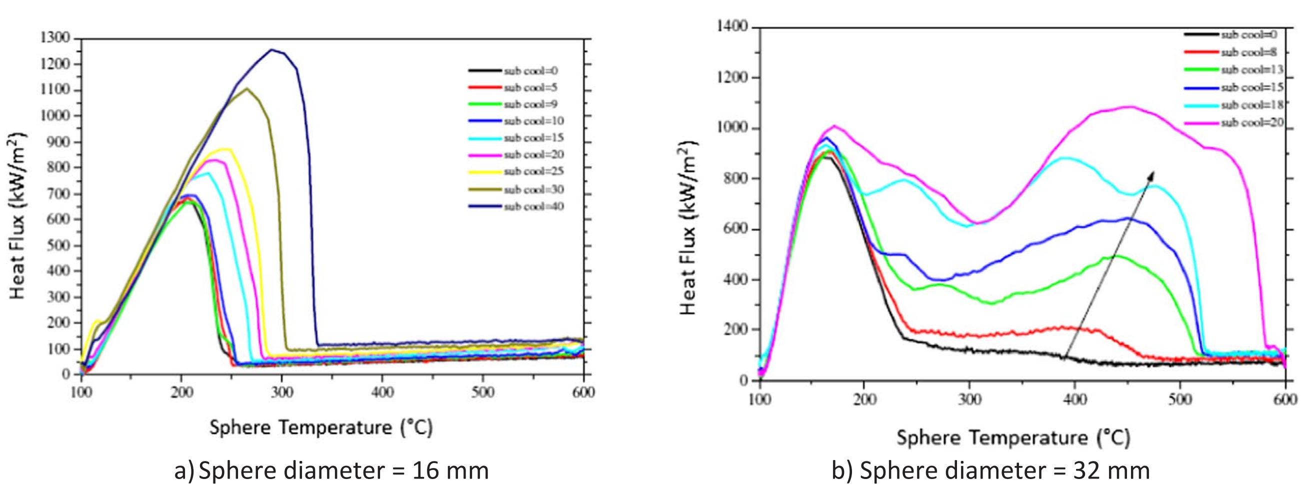

Fig. 3. Sphere heat flux versus sphere temperature during quenching for different water subcoolings (Figs. 6 and 7 from [7]).