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Influence of Non-Condensable Gas-Dust Mixture on Direct Contact Condensation of Steam at Atmospheric Pressure

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ABSTRACT

At the Department of Civil and Industrial Engineering (DICI) of the University of Pisa, an experimental research program, funded by ITER Organization, concerning steam direct condensation in a flux containing also non-condensable gas and dust, was carried out. This mixture of fluids and dust is injected into the ITER Pressure Suppression Tanks during a Loss of Coolant Accident in the Vacuum Vessel. The aim of the research program is to determine the steam condensation efficiency in such conditions. Experimental tests were performed injecting this mixture in a tank partially filled with water. Alumina was used to simulate the actual dust present in the ITER Vacuum Vessel. Mass flow rates, temperature and pressure of the different fluids involved were recorded during the tests.
The steam condensation into the subcooled water pool at a temperature ranging between 20 and 100 °C was investigated to determine the condensation regimes occurring during the mixture injection. The values of the fraction of the energy absorbed by the water and of the average heat transfer coefficient were determined considering pure steam, steam-dust and steam-air–dust injection. The average heat transfer coefficient, determined calculating the steam jet surfaces by means of image elaboration, was compared with empirical correlations.

1 INTRODUCTION

The International Tokamak Experimental Reactor (ITER) manages accidental scenarios in the vacuum vessel, such as Loss Of Coolant Accidents (LOCA) by means a Pressure Suppression System in which the steam is condensed in a subcooled water pool at sub-atmospheric pressure. During the Direct Contact Condensation (DCC) the steam is converted in liquid increasing the pool water temperature and suppressing the Vacuum Vessel pressure. The plasma erosion of the first wall and of the divertor produces mainly activated dust of beryllium and tungsten. Oxygen and isotopes of Hydrogen due to the radiolysis or thermolysis of the water are non-condensable gas produced during a LOCA. In this accidental scenario, the steam carries dust and gases from vacuum vessel to the Pressure Suppression Tanks.

At the Department of Civil and Industrial Engineering (DICI) of the University of Pisa, an experimental research program, funded by ITER Organization, for the qualification of the Pressure Suppression System was carried out [1-5].

Several authors elaborated empirical correlations for the average heat transfer coefficient, performing direct contact condensation at atmospheric pressure with horizontal nozzle.

Kim, H. Y. et al. [6] elaborated the following correlation for the average heat transfer coefficient, h_{ave}:

$$h_{ave} = 1.4453 * C_p * G_m * B^{0.03587} (\frac{G}{G_m})^{0.13315} \quad (1)$$

being $B = c_p * \frac{\Delta T_{sub}}{h_{fg}}$ the dimensionless condensation driving potential; $\Delta T_{sub} = T_{sat} - T_p$, the subcooling, C_p ($\frac{kJ}{kg\,°C}$), the isobaric heat capacity; G_m and G ($\frac{kg}{m^2\,s}$), the critical and the actual steam mass flux; T_{sat} (°C) the pool water saturation temperature, h_{fg} ($\frac{kJ}{kg}$), the latent heat of vaporization, T_p (°C), the temperature of the pool water.

The correlation (1) was determined in tests at the following conditions: G= 250-1188 $\frac{kg}{m^2 s}$, T_p= 35-80 °C and nozzle diameter D_{hole}= 5-20 mm
A similar correlation was elaborated by Kim, Y.S. et al. [7] performing tests at the following conditions: G= 0-1500 $\frac{kg}{m^2 s}$, T_p= 13-87 °C and nozzle diameter D_{hole}= 1.35-10.85 mm

$$h_{ave} = 1.3583 * C_p * G_m * B^{0.0405} (\frac{G}{G_m})^{0.3714} \quad (2)$$

The correlation (1) was obtained in experimental conditions which do not fit completely the tests performed at University of Pisa. It gives values of h_{ave} 15 % greater than those of the correlation (2).

The aim of this work is to evaluate the influence of dust and non-condensable gas on the condensation efficiency as well as on the average heat transfer coefficient.

Alumina (Al_2O_3) was used as simulant of the dust with a granulometry very similar to the beryllium dust [8]. In this paper the results of fourteen condensation tests performed injecting in the prismatic tank pure steam, steam-dust and steam-air-dust were analysed.

2 EXPERIMENTAL RIG

The experimental rig, built at the "B. Guerrini" Laboratory of the University of Pisa, is made of a condensation prismatic tank (Figure 1) with a horizontal sparger located inside; a superheated steam supply system; two tanks containing pressurized air (up to 10 bar); a degassed water supply system; a dust dosing system; a discharge line with a demister and HEPA filters; a data acquisition and control system and a visualization and video recording system.

Figure 1: Prismatic tank

The prismatic tank (width= 1460 mm, length= 2300 mm and height= 990 mm), insulated by rock wool, is filled with 2.230 m^3 of water. The experimental tests were performed injecting steam, dust and air through a horizontal nozzle into the water at the following conditions:

- dust: mass flow rate ranging between 0.67-1.11 $\frac{g}{s}$ and total masses equal to 3, 6, 12 kg, respectively
- steam: mass flow rate ranging between 11.5-25 $\frac{g}{s}$, T=150 °C, P=1.5 bar
- air: mass flow rate and temperature ranging between 4.9-7.2 $\frac{g}{s}$ and 67-72 °C
- pool water: temperature ranging between 22.7-100 °C, P=1.013 bar, head=0.665 m
- horizontal nozzle having 10 mm of diameter (Figure 2).

Pressure and temperature sensors were located along the injection lines and in the water pool.

The images were captured by two videocameras: positioned one on the lateral side of the condensation tank and one on the top.

Figure 2: Nozzle of the experimental rig

3 TEST RESULTS

Table 1 lists the results of fourteen condensation tests corresponding at four different temperatures (45 °C, 60 °C, 80 °C and 96 °C) performed with steam, steam-dust and steam-air-dust.

Table 1: Results of condensation tests (S=Pure steam, SD=Steam and dust mixture, SDA =Steam, air and dust mixture)

N°	Test-flag	Regime	T_p [°C]	T_s [°C]	G $[\frac{kg}{m^2 s}]$	C_{DUST} $[\frac{g}{l}]$	$\dot{m}_{air}$ $[\frac{g}{s}]$	WEF [%]	h_{ave} $[\frac{kW}{m^2 °C}]$
1	S45	CO	45	108.3	168.1	0.00	0	91.42	920.78
2	S60	CO	60	108.3	168.5	0.00	0	87.01	812.38
3	S80	CO	80	108.3	169.7	0.00	0	78.21	577.5
4	S96	No apparent condensation	96	108.9	174.5	0.00	0	35.42	-
5	SD45	CO	45	108.2	163.3	0.121	0	89.58	659.29
6	SD60	CO	60	108.5	160.7	0.24	0	83.57	523.16
7	SD80-1	CO	80	108.7	165.6	0.48	0	82.80	575.22
8	SD96	No apparent condensation	96	108.8	163.5	0.63	0	75.70	-
9	SD80-2	CO	80	108.7	165.2	0.33	0	84.41	553.74
10	SD80	CO	80	108.7	163.5	0.86	0	91.59	548
11	SD60-1	CO	60	108.7	167.7	0.8	0	84.79	616.98
12	SDA45	CO	45	100.2	70.4	0.39	5.1	94.78	-
13	SDA60	CO	60	100.3	60.9	0.97	6.6	77.96	-
14	SDA80	CO	80	100.5	48.5	1.84	5.88	60.87	-

Figure 3 illustrates the test results in the map of the condensation regimes elaborated by Cho et. al. [9]. The tests are located in the middle of the condensation oscillation (CO) area and near the boundary between this zone and the bubbling condensation oscillation (BCO) area. Two tests are in the non-apparent condensation area. In this case, the pool water temperature is greater than 90 °C.

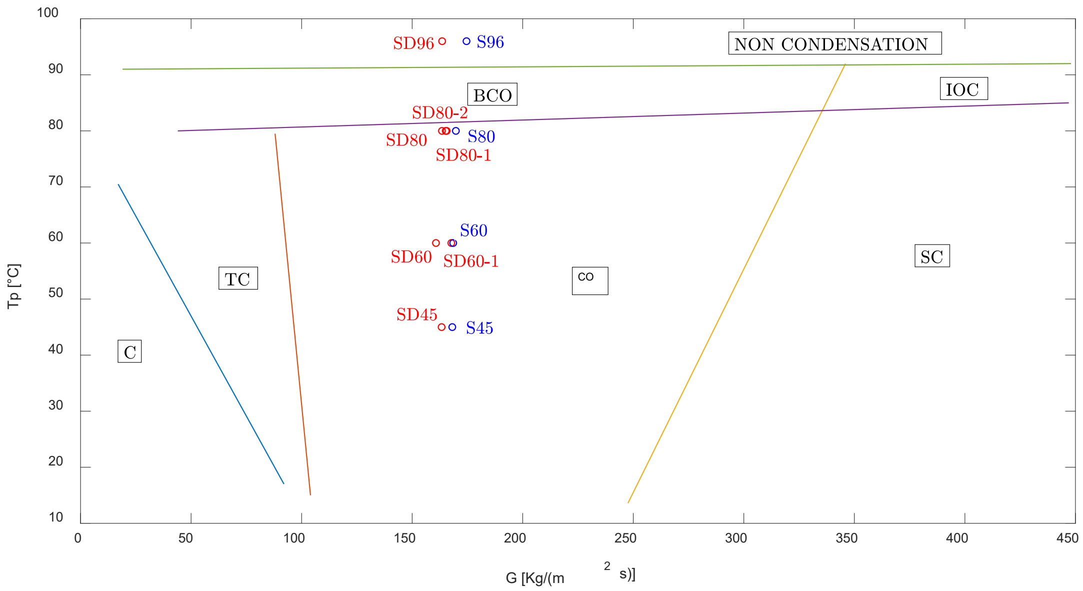
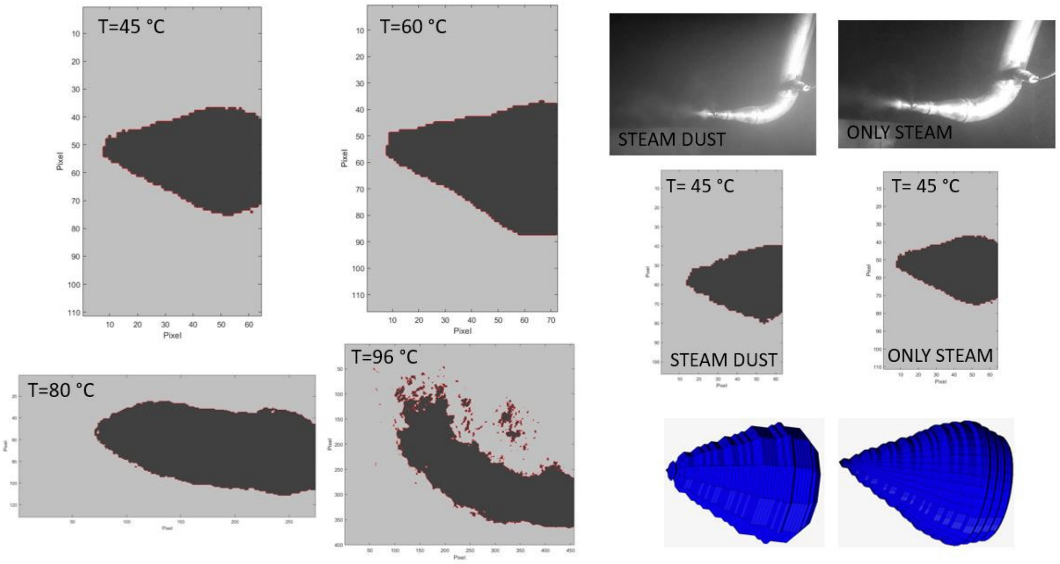


Figure 3: Test condensation regimes (SD= Steam-Dust, S=Steam, SDA= Steam-Dust-Air, C= Chugging, T= Transitional chugging, CO = Condensation oscillation, SC= Stable condensation, BCO= Bubbling condensation oscillation, IOC= Interfacial oscillation condensation)

The elaboration of steam jet plume profiles by means MATLAB software [10], was permitted to estimate the area of the steam surface in the case of pure steam injection. In the case of injection of dust and steam, few grams of dust reduce the water transparency and an image elaboration is possible only in the first instants of the test. Figure 4 shows the jet plume profiles corresponding at pure steam and steam-dust tests at different water temperatures.



(a) (b)

Figure 4: Jet plume profiles of pure steam at different temperatures (a); comparison of jet plume profiles with or without dust (b)

The determination of the jet plume area permits to calculate the average heat transfer coefficient of the direct contact condensation, h_{ave} ($\frac{kW}{m^2\,°C}$), by means of the following formula:

$$h_{ave} = \frac{P_{steam}}{A_i * (T_s - T_p)} \tag{3}$$

being A_i (m^2) the area of the jet plume, T_s (°C) the steam temperature, P_{steam} (kW) the steam power released in the water.

The experimental average heat transfer coefficients were compared with the empirical correlation (2), previously reported (Figure 5). The solid line $h_{ave-exp}$=$h_{ave-theor}$ corresponds to the equality of experimental and empirical values (line at 45 °). The comparison shows a difference of about 16 % for the tests with pure steam and water temperature up to 60 °C (circle marks). At greater water temperatures, the experimental values are smaller than the theoretical one (577.5 and 1017 $\frac{kW}{m^2\,°C}$, respectively). The injection of dust decreases the average heat transfer coefficient of about 30 % up to 60 °C (triangle marks). For greater water temperature, the h_{ave} for pure steam condensation is not influenced by the dust. It is worth to note that h_{ave} for the steam-dust condensation is almost independent by the water temperature.

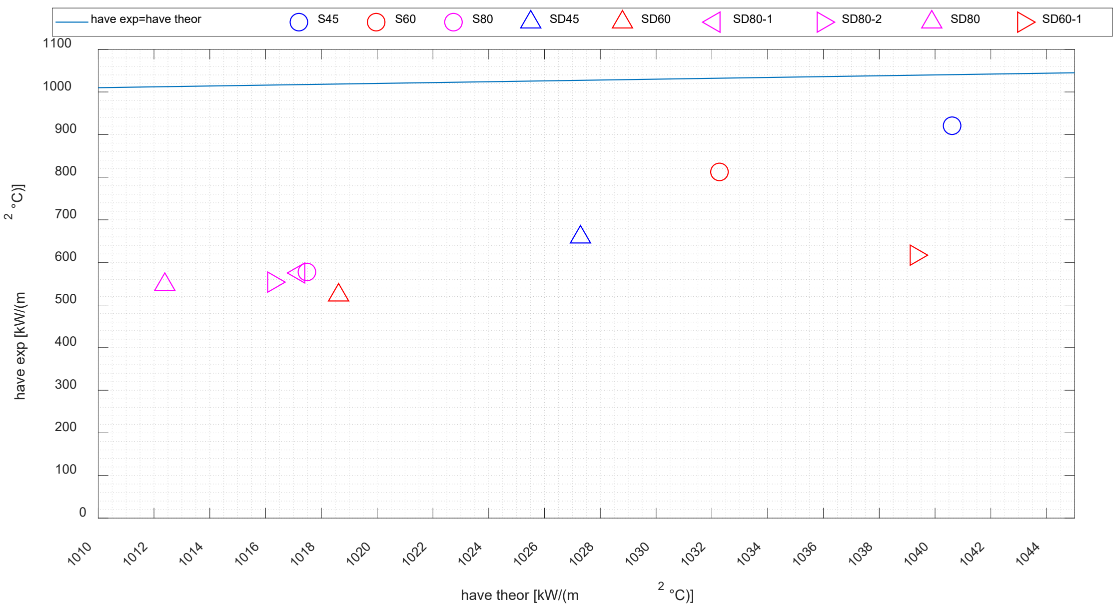


Figure 5: Comparison between experimental and empirical h_{ave} (correlation (2)) corresponding to the injection of steam and steam-dust

An interesting parameter for determining the influence of the dust and of the non-condensable gas on the steam condensation is the energy fraction absorbed by the water, WEF, versus the water temperature:

$$WEF\ [\%] = \frac{E_p}{E_i} * 100 \tag{4}$$

being E_p the absorbed energy in the water at an average temperature T_p in a time interval Δt=400 s; E_i the steam energy released in the same time interval Δt.

The total steam energy injected in the water pool is spread in several parts:

- energy absorbed by the water
- steam flux exiting from the container
- energy absorbed by the metallic walls of container and lost through the insulation
- increase of dust temperature
- increase of air temperature

Figure 6 shows the percentage of absorbed energy in the water versus the water temperature for the three examined cases. In the case of pure steam, about 91 % of steam energy is absorbed by the water up to 45 °C. This fraction is reduced at 35 % at 96 °C. The presence of dust reduces a bit the energy absorbed by the water up to 60 °C, but increases it for greater water temperatures. The dust works as condensation nucleus, improving the heat transfer between steam and water. WEF for steam-dust flux is practically constant, ranging between 89-75 % for water temperature varying between 45-96 °C. The air decreases the effect of the dust, decreasing the energy absorbed by the water because a stream of steam bubbles is carried by the air flux outside the tank.

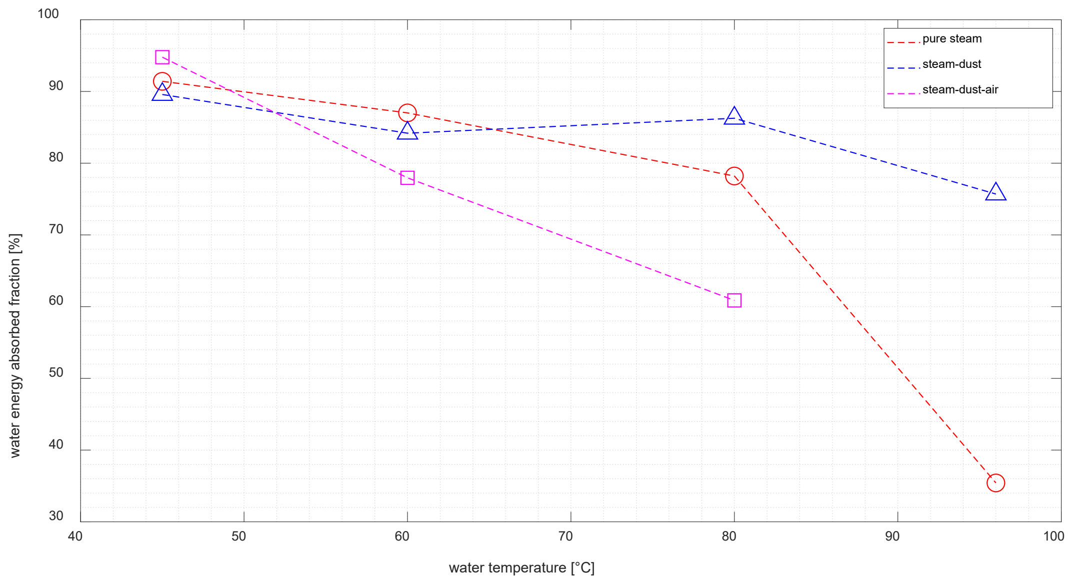


Figure 6: Water energy absorbed fraction

4 DISCUSSION OF THE RESULTS AND CONCLUSIONS

The experimental research program carried out at the University of Pisa has the aim to study the direct contact condensation of steam in presence of dust and non-condensable gas. Some operation conditions which could verify in the Pressure Suppression System (PSS) of ITER were taken into consideration. In particular, the value of the steam mass flow rate per unit of injection area, G, which determines no stable regimes (Condensation Oscillation, Bubbling Condensation Oscillation) for the entire range of water temperature (40-100 °C). These no stable condensation regimes are similar to those foreseen in the accidental scenarios of ITER.

Empirical correlations (equation 1) and 2)) for determining the average heat transfer coefficient were obtained for a wide range of G and they underestimate the dependence on the water temperature, above all for temperature greater than 80 °C. This underestimation depends on the exponent of B, the dimensionless condensation driving potential. The injection of dust decreases the average heat transfer coefficient of about 30 % up to 60 °C.

The influence of the dust and of the non-condensable gas on the steam condensation was evaluated considering the fraction of steam energy absorbed by the water, WEF, versus the water temperature. In the case of pure steam, about 91 % of steam energy is absorbed by the water up to 45 °C. This fraction is reduced at 35 % at 96 °C. The presence of dust reduces a bit the energy absorbed by the water up to 60 °C, but increases it for greater water temperatures. The air decreases the effect of the dust. Actually, the air creates turbulence, decreasing the effect of the dust as condensation nucleus.

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