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Experimental study on heat transfer inside a blocked region of a rod bundle during a LOCA

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ABSTRACT

In the course of a LOCA accident, the fuel rod can be deformed and thus, it is important to be able to predict the coolability of these regions. One issue of a LOCA is the coolability of the blockage zone.
In order to experimentally analyze the influences of the cladding deformation on the heat transfer, different vertical tubes are used to study different blockage ratio. A first section of constant diameter equal to the hydraulic diameter of a sub-channel PWR is followed by a smaller part which is representative of a significant deformation (blockage ratio between 61% and 90%), with different lengths of this section. In the last part of the tube, the hydraulic diameter gradually increases to represent the output of the ballooned area and ends with the same diameter as the inlet.
The two-phase flow injected is a controlled flow of superheated steam with polydispersed water droplets produced by a piezoelectric injector. The tube (i.e. test section) will be heated up to 800°C to be representative of the temperature of the fuel rod during the reflood. At the inlet and outlet of the deformed zone of the tube, measurements will be carried out using optical metrology techniques such as Phase Doppler Anemometry (PDA) and Laser Induced Fluorescence (LIF) to characterize the droplet's flow. Along the deformed region, temperature measurements will be performed using infrared thermography.
This paper presents the test section with its instrumentation. The different thermal hydraulic parameters will be complementary to the COAL experiments where knowledge at the sub-channel scale to characterize steam/droplets flow and heat transfer with the purpose to better understand the coolability during a LOCA.

KEYWORDS

Coolability, blockage, LOCA, Heat transfer, LIF, PDA

1. INTRODUCTION

During a Loss Of Coolant Accident (LOCA), partial or even complete drying of the fuel assemblies may occur. In these conditions, the fuel temperature increases and the coolant pressure drops in the reactor core may lead to significant deformation or rupture of the fuel rod cladding (Fig. 1). Depending on the fuel rod conditions during such an accident, extensive fuel fragmentation may occur, leading to some fuel relocation within the ballooned area. Depending on the size and the distribution of the ballooned areas within the fuel bundle, the core coolability might be impaired.

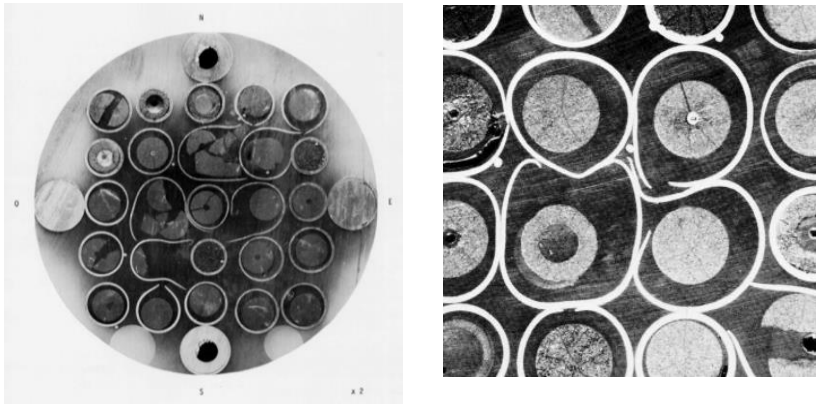


Fig. 1. Bundle of deformed fuel rods; Phebus LOCA experiments (1983)

The French Institute for Radiological Protection and Nuclear Safety (i.e. IRSN) has launched, with the support of ANR (Agence Nationale de la Recherche), the PERFROI project [1], [2] for a six year period (2014-2019) with two main axes: thermal mechanics (axis 1) and thermal hydraulics (axis 2). The COAL experiments (in the axis 2), focuses on the outstanding issue of the coolability of a partially deformed fuel assembly [3], in particular the study of the thermal hydraulic behavior in the ballooned area, during reflooding phase by water injection with the safety systems.
To understand and analyze the heat transfer at the fuel assembly scale, more detailed research activities foreseen in the laboratory of the Lorraine University will focus on the characterization of two phase flows with heat transfer [2] in deformed structures at the sub-channel scale using specific instrumentation such as Laser Induced Fluorescence (LIF) and Phase Doppler Anemometry (PDA) technics.

2. THERMAL HYDRAULICS BEHAVIOR OF A PARTIALLY BLOCKED CORE ZONE DURING THE REFLOODING PHASE

In order to limit the damage of the fuel assembly, the safety water injection system is activated to cool down and ensure the state of the reactor during a LOCA accident. It corresponds to the reflooding phase of the accident. The subcooled liquid flows in the pipe of the primary circuit of the reactor, then in the annular space of the vessel and finally reaches the bottom of the core. When the liquid enter goes in the core, a liquid level appears (called quench front) and three thermal hydraulic zones may be identified (Fig. 2).

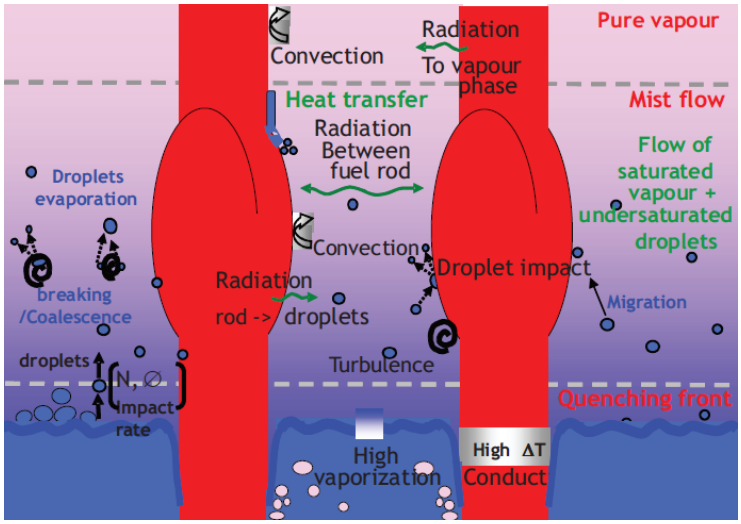


Fig. 2. Thermal-hydraulic phenomena occurring during the reflooding phase of a LOCA at the sub-channel scale [4]

- ✓ **Quenching front zone:** Within this area, boiling mechanisms occur: Firstly nucleate boiling in the lower area from the front with steam bubble formation. Above, the water surrounding the rod claddings undergoes a film boiling regime. In this level, a vapor film is formed due to the high temperature of the rod cladding. Due to the turbulence of the steam flow near the quenching front and because of the bubble burst mechanism [5], water droplets are formed above the quenching front and carried by the vapor flow.

- ✓ **Two-phase vapor/drops zone (Mist-flow)**: Constituted by a mixture of droplets and steam downstream the quenching flow. This two-phase flow can be described by distributions of droplets (size and velocity); the droplets, at saturation temperature, are carried by the vapor flow. In this zone the cooling is mainly due to vapor-wall convection, vapor-wall and droplet-wall radiation and finally, direct droplet-wall impacts. It can be noticed that vapor-droplet convection is also important because it may change the overall vapor flow. The two-phase droplet/steam has thus a meaningful role in the coolability of the blocked zone.

  According with some studies about LOCA [4], [6], [7] the droplet diameters along the deformed region are in the range of 50µm-1mm, and their velocities varying from 1 to 30m/s; droplet volume fraction may vary from 10^{-4} to 10^{-2}. Droplet temperature is generally close to saturation. Vapor temperature can be in the range of 100°C-800°C with velocities up to 30 m/s. Wall temperature is above 600°C which means being above the Leidenfrost point.
  According with the Phebus LOCA experiments, local blockage ratios during a LOCA can reach values up 90% (Fig. 1) (with ballooned heights in the range of 50-300 mm

- ✓ **Pure vapor zone:** Far from quenching front zone, there are no more droplets and heat transfer is only due to forced convection and radiation between steam and rod bundles.

Even if many experiments have been performed on reflooding of ballooned fuel bundle (FEBA, SEFLEX, THETIS, ACHILLES, FLECHT, CEGB) [6] there is no, till now, a test bench specifically dedicated to study the heat transfers in the blocked zone between the heated wall and a steam/droplet flow.
With the aim to analyze the cooling effects of two-phase flow in a partially deformed fuel assembly, some separated works have been done to characterize the heat transfer between the dispersed droplets and heated deformed claddings and are described below.

2.1 Impact droplet-wall heat transfer

For the flow regime during a reflooding phase of LOCA accident, impact of drops with the rod claddings is expected. According to LOCA literature, the heat transfer by direct droplet-wall impact is of the same order of magnitude than the convective steam/wall heat transfer and should therefore be considered [8]. The impact regimes are function of diameter and velocity of the droplets and the wall temperature. To characterize it, the Weber number is used; in LOCA conditions, this number is expected to be less than 60 what implies a droplet rebound [9]. Wall temperature is well above the Leidenfrost temperature, this fact makes the drops don't touch directly the wall surface due to formation of a vapor layer. This layer thermally insulates the droplet and minimizes the loss of heat from the surface at the impact.

Some works have been focused on the dynamics and the heat exchange between a droplet impacting a heated surface [10], [11]. Recently, a set-up has been developed to accurately measure the heat transfer between a single droplet and a hot wall for conditions close to LOCA [6], [12], [13]. These experiments were performed with droplet in the range of 80-300 µm impinging a thin nickel disk (500µm) heated up to 600°C. The energy extracted by the droplet from the heated wall has been modelled to be dependent on Weber and Reynolds numbers of the droplets and wall temperature [6]. This energy is deduced by coupling temperature measurements, droplets dynamics and a semi-analytical inverse heat conduction model [14].

This model accounts for the spreading of the droplet as a function of time and for the vapor flow beneath the droplet.



Fig. 3. Droplet-wall interaction in the bouncing regime (Weber < 40) [9]

2.2 Radiation droplet-wall heat transfer

The quantity of heat absorbed by the droplets depend on the droplet size, droplet volume fraction, droplet temperature and wavelength of the incident energy [5]. Estimations of the radiative heat transfer along the rod cladding have shown that this mechanism can take part up to 30% of wall cooling enhancing the evaporation of droplets.

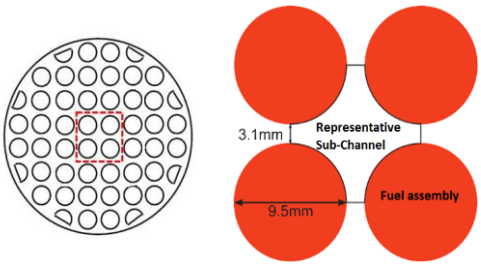
In order to quantify the heat transfer by radiation, a numerical study financed by IRSN was carried out on radiative transfer in a two-phase flow related to a LOCA, involving radiative properties computed for the mixing of vapor and droplets encountered in such a case using Neptune-CFD [15], [16]. The results of these experiments helped to refine and validate the heat exchange models implemented in some codes (Neptune_CFD, DRACCAR [17]) to well understand the physical reflooding phenomena.

3. EXPERIMENTAL SET-UP

The objective of the set-up is to characterize the two-phase flow (mist flow of vapor and droplets) and to measure the heat transfer in the deformed structures. The proposed approach is expected to validate the models already developed on flow and heat transfer between wall and fluid and mainly understand and quantify the heat transfer by radiation and impacts between the dispersed droplet and the heated walls.

3.1 Geometrical features

In order to reproduce the fluid flow characteristics in a representative sub channel scale, a vertical Venturi tube configuration has been developed with an equivalent hydraulic diameter equal to a representative sub-channel section of a PWR reactor:



$$D_h = 4\frac{cross\ sectional\ area}{wetted\ \ perimeter}$$

$$D_h = 11.8\ mm$$

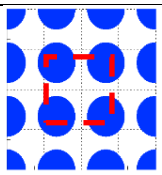
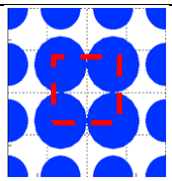
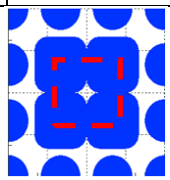
Fig. 4. Geometry for PWR representative sub-channel

In a PWR, the rod claddings are made of Zircaloy, a zirconium alloy which is used because of its low absorption cross-section of thermal neutrons and corrosion resistance. In order to avoid the zirconium oxidation and the consequent released of hydrogen gas when reacting with steam at high temperature, our tube test is made of Inconel-625 having three different sections:

- The first part has a constant diameter equal to the hydraulic diameter of a sub-channel PWR. The thickness of the tube is 0.57 mm;
- The second part is representative of a partially coplanar blocked sub-channel section. Different lengths will be considered (100mm and 300 mm). Thicknesses of the tube have to be changed in order to have a constant electric resistance;
- In the last part, the hydraulic diameter gradually increases to represent the output of the ballooned area and will end with a cylindrical portion of the same diameter, thickness and height as the first part.

5 geometrical configurations will be tested (see Table 1):

Table 1. Geometrical configurations to be tested

	Config. n°1	Config. n°2	Config. n°3	Config. n°4	Config. n°5
Blockage ratio	0%	61%	61%	90%	90%
Equivalent hydraulic diameter	11.8 mm	7.35 mm	7.35 mm	3.72 mm	3.72 mm
Height of the ballooned area	-	100 mm	300 mm	100 mm	300 mm
Thickness	0.57 mm	0.86 mm	0.86 mm	1.38 mm	1.38 mm
					

The configuration n°1 corresponds to the reference COAL bundle B0 and the last configuration n°5 to the COAL bundle B2 including the largest blocked area with the so-called long ballooning [17].

3.2 The thermal hydraulic tube test

The experimental test will be performed during the next two years. Fig. 5 describes the thermal-hydraulic circuit.
The scenario is divided in two phases as classical “Reflooding experiments” already performed:

1. Heat up phase in atmospheric condition: The venturi tube is heated up to 800°C by Joule effect using a 5kW electric generator. The power flanges are located at 50 mm before and after the blocked area; when the operating temperature is reached, the electrical power supply is interrupted and injection of the two-phase flow starts.

2. Cooling by two-phase flow injection: In order to represent the two-phase flow during a reflooding, drops and steam are injected downstream the tube and mixed in a chamber designed to have a homogenous flow of vapor. The evolution of the cooling is followed using optical techniques located along the representative blocked section: Phase Doppler Anemometry (PDA) and Laser Induced Fluorescence (LIF) to measure droplet properties such as velocity, diameter and temperature at the entrance and exit of the blocked section through optical access in quartz; infrared camera is facing the blocked section in order to measure the temperature field.

3.3 Thermal hydraulics features

With the purpose to simulate the flow conditions during the reflooding, a two-phase flow of droplets and superheated steam is injected downstream the tube.

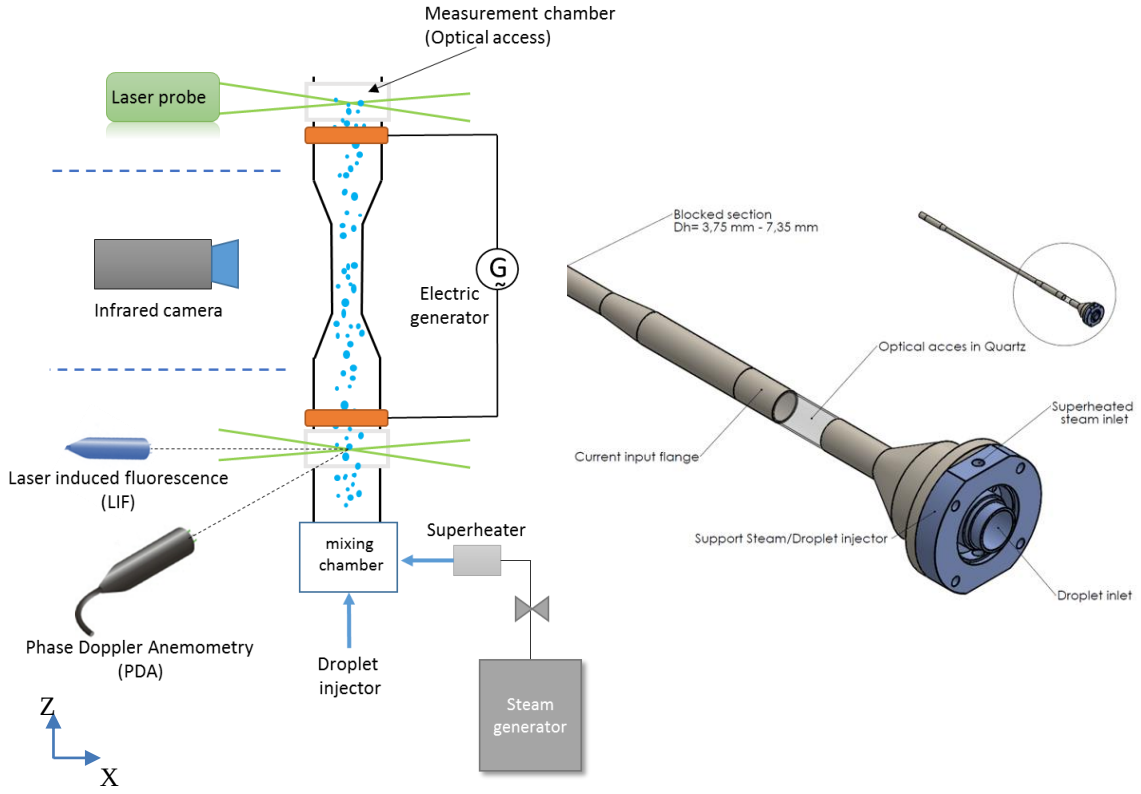


Fig. 5. Scheme of thermal hydraulic circuit of the experimental test facility

For the droplets flow, there are experiences for mono-dispersed and poly-dispersed droplets. For the first case, droplets are injected at high frequency thanks to a purpose-designed piezoelectric nozzle where the droplet frequency, velocity (V) and size ($D_{droplet}$) at injection can be adjusted; for the second case, dense sprays injectors are used in order to analyze the effect of the distribution. The steam flow is generated by a steam generator which delivers a maximum mass flow rate up to 8.4 kg/h. At the exit of the generator, a heater is located in order to increase the steam temperature up to 300°C.
The Venturi tube is heated at high temperature by Joule effect using an electric generator. To achieve this, two flanges are located before and after the contracted section of the tube. According with theoretical results taking into account the heat exchange by convection and radiation with the external air and the internal two-phase flow, an electric current near to 250A is used to heat the tube to 800°C using an electrical power of approximately 1.8 kW.
Table 2 shows the range of thermal hydraulics parameters to be analyzed along the experimental test:

Table 2. Thermal hydraulic conditions during reflooding scenario

Inlet steam velocity	Up to 12 m/s
Inlet steam temperature	100°C - 300°C
Inlet droplet velocity	Up to 10 m/s
Inlet droplet temperature	From room to saturation temperature
Cladding temperature before reflooding	600°C to 800°C
Electric power	5 kW
Flow mass by steam generator	Up to 8.4 Kg/h

3.4 Experimental diagnostics

Measurements are provided by specifics technics such as Phase Doppler Anemometry, Infrared cameras and Laser Induced fluorescence.

- **Phase Doppler Anemometry PDA:**

The properties of the droplet flow (velocity and diameter) are obtained using a Phase Doppler system (PDA). The Phase Doppler system (Fig. 6) is a 2D commercial classic PDA manufactured by Dantec-Dynamics®. An argon ion laser, (λ = 514.5 nm), is used to perform velocity (along the Z-direction) and diameter measurements. PDA excitation volume is formed using a LDA transmitter probe (Dantec-Dynamics Fiber-Flow® probe) aligned along the X-direction .The system includes a classic PDA receiver which operates in the first refraction mode. Finally the signal is analyzed with the use of a P80 signal processor.

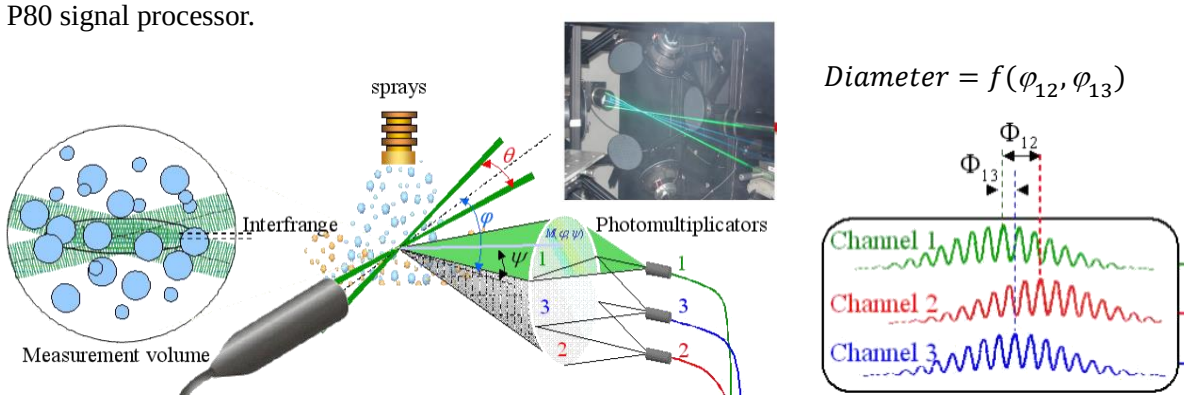


Fig. 6. PDA technics

- **Infrared camera:**

The temperature field along the blocked section of the Venturi tube is estimated thanks to an infrared camera. The infrared camera (Cedip® Jade III) is built with a focal plane array photonics detectors (InSb) working in the spectral range [3–5 µm] and it's equipped with a narrow-bandwidth [3.97–4.01 µm] spectral filter to fit with the expected experimental temperature range. The spatial resolution is 320x240 pixels/ frame. A thermocouple is required for the calibration of the emissivity of the wall. This measurement is required to calibrate the whole measurement chain. The calibration is performed by heating the tube up to 800 °C and by recording simultaneously the infrared signal and the temperature measured by the thermocouple, while the tube is cooling down naturally (radiative, convective heat transfer and residual conduction).

- **Laser Induced fluorescence (LIF):**

The temperature of the droplets is performed using the LIF technique (Fig. 7). This technique already demonstrated its ability to characterize the temperature of droplets in various conditions [18], [19], [20].

This technique is based on the measurement of the fluorescence intensity of a temperature-sensitive fluorescent dye at a low concentration. For our case, sulforhodamine-B is used because of its sensibility to variation of temperature and for its solubility in water.

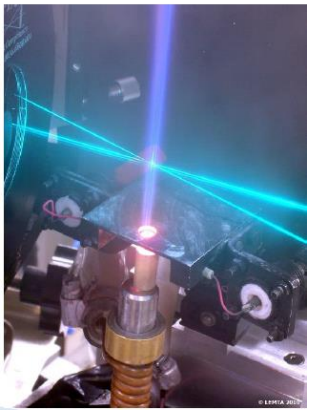


Fig. 7. LIF technics

The fluorescence is induced by the green line of an argon ion laser, the same used for PDA measurement. The intensity of the fluorescence signal detected on a given spectral band (i) can be expressed as :

$$I_{fi}(T) = K_{opt,i}K_{Spec,i}V_c I_0 C * exp\left(\frac{\beta_i}{T}\right) \quad (1)$$

Where I_0 is the local laser excitation intensity; C, the fluorescent dye concentration; T, the absolute temperature and V_c, the collection volume of the fluorescence. $K_{opt,i}, K_{Spec,i}$ are parameters influenced, respectively, by the optical layout and the fluorescence properties of the fluorescent tracers and β_i, a coefficient determined experimentally which corresponds to the temperature sensitivity of the fluorescence signal detected on the spectral band i. To properly measure the temperature of a droplet, the influence of the unknown parameters (C, V_c and I_o) must be removed. To achieve it, a second intensity is detected simultaneously in a spectral band which the temperature sensitivity is sufficiently different compared with the first one.

According to Eq (1), it is possible to derive a ratio between the intensities collected on each spectral band:

$$R_{12} = f(T) = \frac{I_{f1}}{I_{f2}} = \frac{K_{opt,1}K_{Spec,1}f_1(T)}{K_{opt,2}K_{Spec,2}f_2(T)} = \frac{K_{opt,1}K_{Spec,1}}{K_{opt,2}K_{Spec,2}} e^{\frac{\beta 12}{T}} \quad (2)$$

Finally, a single reference R_{120} measurement at a known temperature, To, was used to eliminate both constants Kopt,i and Kspec,i in Eq. (2). The normalized ratio R_{12}/R_{120} is given by following:

$$R_{12}/\,R_{120} = \frac{f_{12}(T)}{f_{120}(T)} \quad (3)$$

The precedent expressions are valid to analyze mono-dispersed droplets. A recent study highlighted the effect of the droplet diameter on the fluorescence ratio. To account for the effect of the droplet size on the fluorescence ratio and be possible analyze poly-dispersed flows, an empirical function $g_{12}(D)$ was added in Eq (3):

$$R_{12}/\,R_{120} = \frac{f_{12}(T)}{f_{120}(T)} g_{12}(D) \quad (4)$$

In order to determine this unknown function, a third spectral band is used in the analysis. The third spectral band was selected in order to minimize the temperature sensitivity of the ratio R32 represented by the function $f_{32}(T)$

$$R_{32}/\,R_{320} = \frac{f_{32}(T)}{f_{320}(T)} g_{32}(D) \quad (5)$$

An empirical relationship between functions $g_{12}(D)$ and $g_{32}(D)$can be determined experimentally measuring the corresponding normalized fluorescence ratios for several droplet diameters under isothermal conditions.

This result can be easily interpolated using a second-order equation:

$$g_{12}(D) = \alpha g_{32}^2(D) + \beta g_{12}(D) + \gamma \quad (6)$$

Finally, using Eq (4), (5) and (6) it's possibly to determine a correlation which depends only for temperature of droplets:

$$\frac{R_{12}}{R_{120}}\frac{f_{12}(To)}{f_{12}(T)} = \alpha\left(\frac{R_{32}}{R_{320}}\frac{f_{32}(To)}{f_{32}(T)}\right)^2 + \beta\left(\frac{R_{32}}{R_{320}}\frac{f_{32}(To)}{f_{32}(T)}\right) + \gamma \quad (7)$$

Fig. *8* shows the LIF/PDA optical setup:

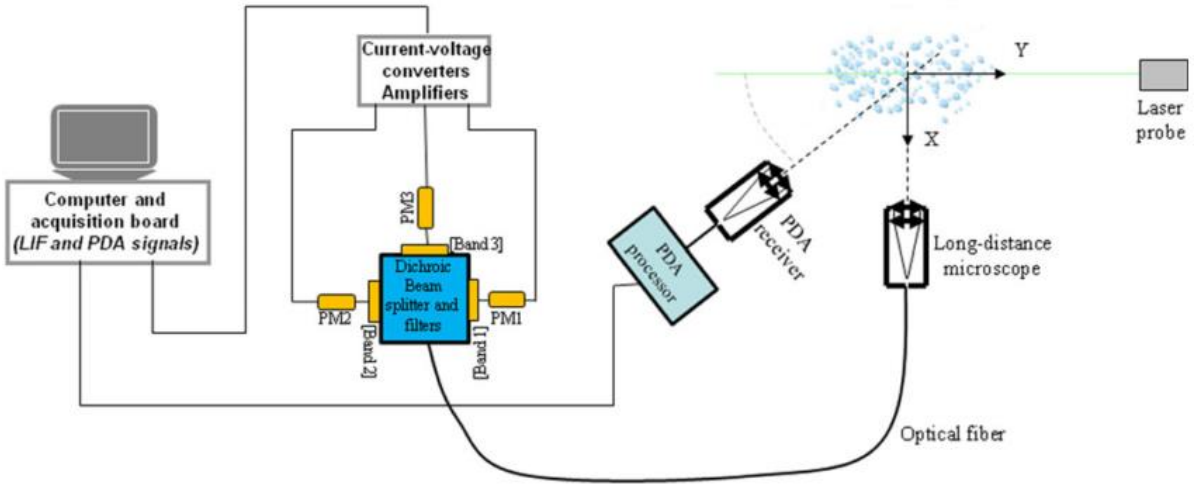


Fig. 8. LIF/PDA optical setup [19]

The collected signal guided by the optical fiber is high-pass filtered (Chroma ®, HQ522LP) in order to remove the light scattered at the laser wavelength. The remaining fluorescence signal is split into the three spectral bands by means of a set of dichroic and interference filters. The fluorescence signal is detected by means of three photomultiplier tubes and digitalized with a frequency of 5 MHz for real time processing. A threshold is fixed significantly above the noise level of the channels of detection.

4. HEAT TRANSFER ANALYSIS

In order to analyze the heat transfer (Fig. 9) between the tube and the two-phase flow along the blocked area, a global energy balance is written. Neglecting conduction losses, global heat transfer balance φ_{global} can be expressed:

$$\varphi_{global} = \varphi_{w\to s} + \varphi_{w\to d} \quad (8)$$

Where the wall/Steam heat transfer $\varphi_{w\to s}$ is due to forced convection $\varphi_{c,w\to s}$ and radiation $\varphi_{r,w\to s}$; and the wall/droplet heat transfer $\varphi_{w\to d}$ is due to radiation $\varphi_{r,w\to d}$ and direct impacts $\varphi_{impacts}$:

$$\varphi_{global} = \varphi_{c,w\to s} + \varphi_{r,w\to s} + \varphi_{r,w\to d} + \varphi_{impacts} \quad (9)$$

This value can be obtained by performing a post-processing of infrared camera data φ_{camera}. Averaging the values along the blocked section, the global heat transfer can be estimated as:,

$$\varphi_{global} \approx \frac{1}{L}\int_0^L \varphi_{camera}(z)\,dz \quad (10)$$

Wall to droplet heat transfer: Droplets exchange with the wall and steam in the following forms:

- Forced Steam/droplet convection $\varphi_{c,\ s\to d}$ and radiation $\varphi_{r,\ s\to d}$
- Wall/droplet radiation $\varphi_{r,w\to d}$
- Wall/droplets direct impacts $\varphi_{impacts}$

$$\varphi_{droplets} = \varphi_{r,w\to d} + \varphi_{impacts} + \varphi_{c,\ s\to d} + \varphi_{r,\ s\to d} \quad (11)$$

Knowing the droplet flow properties upstream and downstream the blocked section, it's possible to determine the global droplet heat exchange using the following equation:

$$\varphi_{droplets} = Cp_l\left(m_{d,2}\,T_{d,2} - m_{d,1}\,T_{d,1}\right) \quad (12)$$

Where Cp_l is the specific heat of water; m_d the droplet flow rate and T_d, the droplet temperature measured in each chamber 1 and 2.
Those parameters can be determined by PDA and LIF measurements.

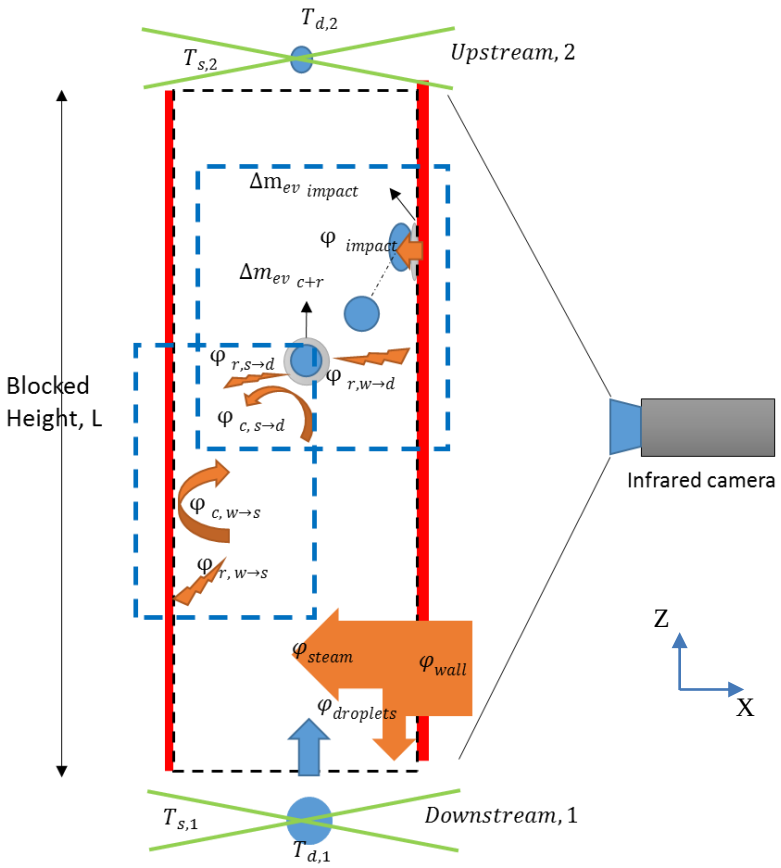


Fig. 9. Scheme of the different heat exchanges along the blocked area of the Venturi tube. (D:Droplet, S:Steam, W:Wall, C:Convection, R:Radiation)

Wall to steam heat transfer: Steam exchange with the wall and droplets in the following forms:

- Forced Steam/droplet convection $\varphi_{c,\ s\to d}$ and radiation $\varphi_{r,\ s\to d}$
- Forced Wall/Steam convection $\varphi_{c,w\to s}$
- Wall/steam radiation $\varphi_{r,w\to s}$

$$\varphi_{steam} = \varphi_{r,w\to s} + \varphi_{c,w\to s} - \varphi_{c,\ s\to d} - \varphi_{r,\ s\to d} \quad (13)$$

Knowing the steam flow properties upstream and downstream the blocked section, it is possible to determine the global steam heat exchange using the following equation:

$$\varphi_{steam} = Cp_s\left(m_{s,2}\,T_{s,2} - m_{s,1}\,T_{s,1}\right) \quad (14)$$

where Cp_s is the specific heat of steam; m_s the steam flow rate and T_s, the steam temperature at the inlet (1) and outlet (2) of the blocked zone.

Due to the droplet evaporation along the blocked zone, there's a difference in the flow rate downstream and upstream the Venturi tube. It can be assumed that the evaporated mass is added to the vapor flow rate. In order to quantify this parameter, we define the next correlations:

$$m_{d,2} = m_{d,1} - m_{ev} \quad ; \quad m_{s,2} = m_{s,1} + m_{ev} \quad (15)$$

Using the precedent expressions (From Eq (8) to Eq (15)), it is possible to estimate the evaporated mass along the blocked section using the following expression:

$$m_{ev} = \frac{\varphi_{wall} - Cp_s(m_{s,2}T_{s,2} - m_{s,1}T_{s,1}) - Cp_l(m_{d,2}T_{d,2} - m_{d,1}T_{d,1})}{Cp_sT_{s,2} - Cp_lT_{d,2}} \quad (16)$$

The precedent energy balance will allow welling understanding the heat transfers along the blocked section for LOCA conditions: It will be possible to determine the contribution of each phase to the core coolability, the evolution of the rod cladding temperature field and consequently the total heat transfer coefficient h and the evaporated liquid mass.

5. CONCLUSIONS

In order to analyze the reflooding phase of deformed fuel bundle and to help the interpretation of the COAL experiments [3] [17], a new set-up has been built. The test channel is representative of a blockage zone with different geometrical configurations. The implementation of innovative non-intrusive optical diagnostics allows investigating the different contributions to the energy balance of the cooling of a representative sub-channel.

A controlled steam/droplet flow is injected in the heated tube; the droplet distribution (velocity, diameter, flow mass) will be characterized using a PDA device. Infrared thermography allows estimating the heat flux removed from the wall by the two-phase steam/droplet flow. Thanks to the Laser Induced Fluorescence LIF device, it is possible to measure the temperature of the droplets flowing inside the Venturi tube and therefore estimate the sensible heat gained by the liquid. An energy balance, taking into account the upstream and downstream measurements, allows estimating the heat transfers for each phase separately and thus evaluate the coolability due to the droplets in a blocked section. The contribution of evaporation to the wall cooling is obtained from the closure of the energy balance.

The proposed approach is expected to validate the models already developed on flow and heat transfer between wall and fluid and mainly understand and quantify the heat transfer by radiation and impacts between the dispersed droplet and the heated walls.

NOMENCLATURE

COAL : COolability of a fuel **A**ssembly during **L**oca
LOCA: Loss Of Coolant Accident
LIF: Laser Induced Fluorescence
PDA: Phase Doppler Anemometry

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