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Radiative transfer during the reflooding step of a LOCA

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ABSTRACT

Within the evaluation of the heat transfer downstream a quench front during the reflood phase of a Loss of Coolant Accident (LOCA) in a nuclear power plant, a numerical study has been conducted on radiative transfer through a vapor–droplet medium. The non-grey behavior of the medium is obvious since it can be optically thin or thick depending on the wavelength. A six wide bands model has been tested, providing a satisfactory accuracy for the description of the radiative properties. Once the radiative properties of the medium computed, they have been introduced in a model solving the radiative heat transfer based on the Improved Differential Approximation. The fluxes and the flux divergence have been computed on a geometry characteristic of the reactor core showing that radiative transfer plays a relevant role, quite as important as convective heat transfer.

1. Introduction

The theoretical study of heat transfer in a dispersed flow is involved in the frame of a variety of domains such as the design of evaporators, spray cooling, liquid fuel spray combustion…. Safety implications of major importance lie in the studies of nuclear power plant core coolabilities subsequent to a large break Loss-of-Coolant Accident. As this safety issue is crucial especially in case of degraded cores involving deformed clads, heat transfer models used to analyze reflood conditions is studied by the French "Institut de Radioprotection et de Sûreté Nucléaire (IRSN)".

In a Pressurized Water Reactor (PWR), during a Loss of Coolant Accident (LOCA), the fuel assemblies are no longer cooled by the surrounding liquid water; the temperature rises to such an extent that some of the initially cylindrical fuel rods could be deformed resulting in ballooned regions of restricted fluid surface area. When cold water is introduced into the core, bottom-up reflooding occurs. At the quench front, a strong evaporation generates a medium of droplets and vapor flowing between hot rods (i.e. a post dry-out dispersed flow regime). The cooling of these ballooned parts of the fuel assemblies, located downstream this quench front, highly depends on this coolant mist flow in a severe thermal non-equilibrium state (over-saturated vapor and quite saturated liquid droplets).

So far, most of the existing models for heat transfer have focused on the cooling of ballooned regions by vapor convection only. However, owing to high temperature levels and the presence of droplets, radiative transfer has been demonstrated to be of major importance through different approaches [1,2]. Yet, this issue is still difficult to address because such an environment is a non-grey absorbing, emitting, non-isotropically scattering and non-homogeneous medium [3] which could be at the same time, at different locations, optically thick or thin. The final objective of the IRSN is the simulation, at the CFD scale with NEPTUNE_CFD [4], of the heat transfer process downstream the quench front. So this particular study, included within the framework of IRSN's R&D

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Nomenclature

Latin symbols

A_1	coefficient of linear anisotropy of scattering (–)
d_p	droplet diameter (m)
f_v	droplet volume fraction (m^3 of water/m^3 of air)
G	integrated intensity ($W\,m^{-2}$)
I_b	blackbody intensity at temperature T ($W\,m^{-2}\,sr^{-1}$)
I	intensity ($W\,m^{-2}\,sr^{-1}$)
J_w	radiosity of the wall ($W\,m^{-2}$)
$\overrightarrow{q}$	radiative flux ($W\,m^{-2}$)
r	position in the medium (m)
S	source term ($W\,m^{-2}\,sr^{-1}$)
T	temperature (K)

Greek symbols

β	extinction coefficient (m^{-1})
ϵ	emissivity (–)
κ	absorption coefficient (m^{-1})
σ	scattering coefficient (m^{-1})
τ	optical thickness (–)
ω	albedo (–)
Ω	solid angle (sr)
$\overrightarrow{\Omega}$	direction

Subscripts, superscripts

m	medium contribution
w	wall contribution
$*$	property computed from P_1 approach
d	droplet property
v	vapor property

List of abbreviations

IDA	Improved Differential Approximation
LOCA	Loss of Coolant Accident
PWR	Pressurized Water Reactor
RTE	Radiative Transfer Equation

programme, addresses the heat and mass transfers, including the coupling with radiative transfer, in a complex 3D geometry filled up with a medium of various optical thicknesses. Hence, it becomes necessary to include a dedicated radiative module to be coupled with a two-phase flow simulation tool which provides a satisfactory compromise between accuracy and computational cost. For that purpose, the Improved Differential Approximation (IDA) has been selected and validated in a companion study [3].

The IDA is an improved version of the well-known P_1 approximation, aimed at better addressing the radiation coming both from the medium and the walls [5]. One well-known weakness of the P_1 approximation is its inaccuracy for cases with optically thin media. The IDA has been demonstrated to improve the accuracy of the RTE solution in various cases [3].

The radiative properties of the two-fluid medium of concern are closely related to two-phase flow conditions and to the core geometry features. Main typical properties are found in the ranges given in Table 1. Hence, preliminary studies on LOCA [6] reveal that the diameters of carried droplets are expected to be in the range of 50 μm and 1 mm and their velocity between 1 and 30 m/s. Their temperature is around the saturation conditions at a quite atmospheric pressure (1–3 bar) whereas the temperature of the surrounding vapor is mainly affected by the wall temperature which could reach 1400 K. Finally, the volumetric fraction of droplets above the quench front varies a lot. Just upstream this front, values between 10^{-4} and 10^{-2} m^3 of water/m^3 have been measured. Furthermore, the radiative paths depend on the core geometry which consists of square rods arrangements. The rod external diameter is 9.5 mm and the pitch between the rod centers is 12.6 mm, but local deformations due to the thermal transient can lead to more complex geometries. In the vertical direction, spacers or mixing grids maintain the rods. They are separated by around 50 cm.

Table 1
Characteristics of the vapor–droplets medium.

Properties	Vapor	Droplets
Temperature (K)	373.15–1073.15	373.15
Volumetric fraction (m^3/m^3)	0.99–0.9999	10^{-4}–10^{-2}
Diameter (μm)	–	50–1000
Pressure (bar)	1.013	–

The present paper aims at simulating radiative transfer in realistic LOCA conditions. In the following sections, the models will be first presented, results will be given on the radative properties of the medium, then simulations of radiative transfer performed in a realistic geometry of a reactor core will be analysed. The part of radiative transfer as compared to other heat transfer modes will be discussed.

2. Modeling

The P_1 Approximation and the Improved Differential Approximation (IDA) used here have been fully described in a dedicated paper [3]. The main useful equations are only recalled here for the sake of brevity.

2.1. P_1 Approximation

The P_1 method provides a solution for the Radiative Transfer Equation (RTE) based on the spherical harmonics