SIMULATION OF RADIATIVE TRANSFER IN A NUCLEAR REACTOR DURING THE REFLOODING STEP IN A LOCA SITUATION

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The Loss Of Coolant Accident (LOCA) is one reference problem, investigated for the design of Pressurized Water Reactors (PWR) by the “Institut de radioprotection et de Sûreté Nucléaire” (IRSN) in the frame of its research program on nuclear fuel safety. In case of a break on the primary cooling loop, the core of the reactor would be damaged due to pressure and water losses and then temperature increase, inducing a deformation of the fuel rods. The safety system provides a reflooding of the reactor core by borated water. During the following transient regime a strong evaporation of water is observed carrying a large amount of water droplets, therefore involving a vapor-droplet medium flowing between the hot rods. One safety criterion is to warrant that the rod temperature does not increase above 1204°C. In the whole heat transfer process, radiative transfer cannot be neglected and it has been evaluated as representing the same magnitude order than the other transfer modes (see Peak [1] or Wong and Hochveiter [2] for example). A finer evaluation of the radiative transfer contribution remains necessary and is the focus of the present work. This has been done in a 2D configuration for the moment but should be extended to a realistic 3D geometry, and combined with a global heat and mass transfer simulation using the thermohydraulic Neptune CFD code. It requires the capacity to perform accurate and efficient computations for the radiative transfer part (with reasonable computational cost). Owing to the medium of interest (vapor and droplets in a flow), the transfer has to be considered through an absorbing, anisotropically scattering, emitting, non grey medium. Such problem of radiative transfer in a 2D geometry has been long investigated with various tools, and with different accuracy levels. The problem can be split into two steps : (i) the computation of the radiative properties (which has been done here considering simple additivity of properties for pure water droplets obtained with the Mie theory [3], and absorbing properties for the vapor using a C-k model [4]); (ii) the solution for the radiative transfer equation itself, for which numerous numerical possibilities are available. Considering the requirement of a solution with a low computational cost, approximate methods have been preferred. The P1 approximation is well known to provide an efficient method, with satisfactory accuracy. However, its accuracy quickly decreases in the case of non optically thick media. A method derived from this P1 approximation has been chosen : the IDA (Improved Differential Approximation), following Modest [3], with the idea that the intensity may be split into two parts as follows :

$$L(\vec{r},\vec{\Omega}) = \frac{J_\omega}{\pi}(\vec{r})e^{-\tau_s} + \int_0^{\tau_s} S^*(\vec{r}+s'\vec{\Omega},\vec{\Omega})e^{-(\tau_s-\tau_s')}d\tau_s'$$

In this relation the left hand side term is the contribution from the walls of radiosity J_w attenuated along the radiation path inside the medium (with τ_s the optical depth along the path s), the right hand side term is the source due to the medium participation all along the path, which is computed with a classical P1 formulation. With this formulation the P1 part warrants a correct computation in the optically thick situation, whereas the boundary contribution is also well addressed, preventing from a potential inaccuracy in the optically thin situation or near the boundaries.

Typical results are presented below, involving characteristic data for the medium of interest : volumetric fraction for droplets (Fv) is ranging between 10^{-2} and 10^{-4} m^3 of water / m^3, droplet size (D_d) is between 50 and 1000 µm, vapor has a pressure between 1 and 2 bars, and temperature range (T_v for the vapor) is between 374 and 1074 K.

Typical radiative properties

Figure 1 and 2 are typical plots of absorption and scattering spectral coefficients. The non grey behavior is obvious, owing to the strong variations with the wavelength. Depending on the droplet size (keeping the same liquid water volumetric fraction), the properties may be governed by vapor (large droplet size case) or droplets (small droplet size case). The reduction of computational cost can be achieved by decreasing the number of wavelength bands integrated in the computation. Tests have been done with 38 bands using the C-k model formalism with a 7 Gaussian point quadrature, a six wide band model, and an equivalent grey model. A database has been also built in order to simply load the properties after a preliminary calculation performed once and for all, instead of computing the properties whenever required. All these tests are carried out currently in order to optimize the computation.

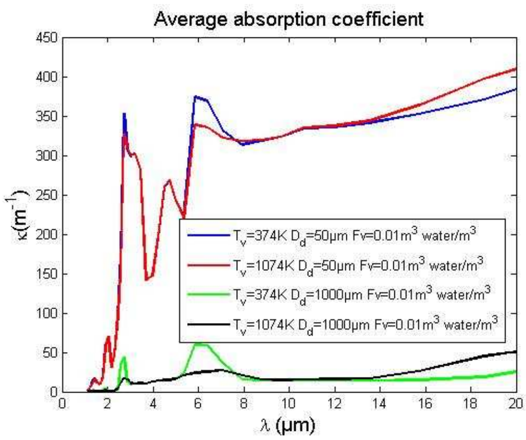

Figure 1 : Absorption coefficients for a representative set of parameters, averaged on each successive spectral bands

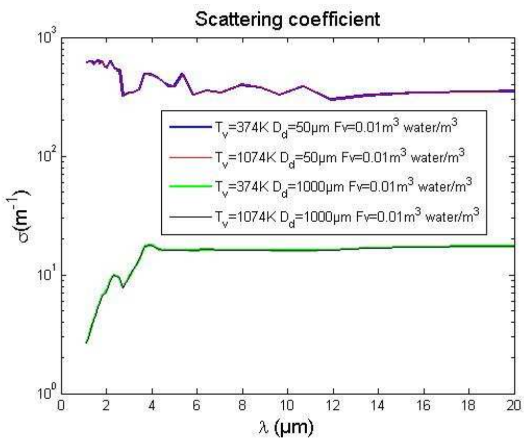

Figure 2 : Scattering coefficients for a representative set of parameters

Radiative flux and flux divergence prediction

Considering a plane transverse to the rod bundle and using the available symmetries, the computation can be done on a 2D domain involving a quarter of a rod and the surrounding medium as presented in Figures 3 and 4. The case of a medium at temperature 373 K with 50µm droplets (volumetric fraction 10^{-2} m^3/m^3) and vapor at 1 bar is simulated, with temperature for the rod set to 1173 K. The radiative flux is presented in Figure 3, and the flux divergence is in Figure 4 (required for coupling the present work with a complete simulation of the problem involving this source term in the energy balance). As can be seen the flux reaches values as high as 80 kW/m^2. The flux is oriented toward the medium with highest values near the rod, as its temperature is higher than in the vapor-droplet surroundings. The flux divergence reaches absolute values of 4.10^7 W/m^3, with negative values as the medium absorption is higher than its emission. Such results are currently further investigated varying the input data for the medium properties, the temperature and pressure conditions and the spectral resolution of the model.

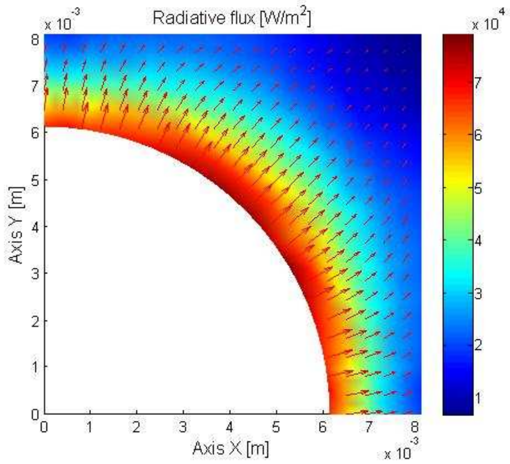

Figure 3 : Radiative flux

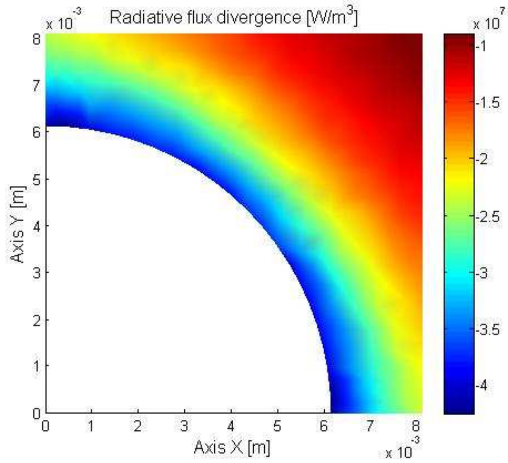

Figure 4 :Radiative flux divergence

CONCLUSION

The radiative transfer problem through a vapor-droplet medium near a solid boundary has been addressed in a case close to a LOCA situation in a nuclear reactor. Radiative properties have been obtained combining the Mie theory and a C-k model. The radiative transfer solution has been computed using the IDA derived from the classical P1 formulation. Results indicate a wide range of possible properties for the medium, depending on the input data for the vapor and the droplet characteristics. Radiative fluxes as high as 80 kW/m^2 have been found, confirming the important role of this heat transfer mode, which cannot be neglected. The work in progress deals with the extension of the present method to a realistic 3D geometry, as the rod temperature is also varying along the flow. Optimization of the numerical method will be sought considering the required coupling of the radiative transfer model with the global simulation of heat and mass transfer through the rod bundle.

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