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Correction

Article title: Determination of the Gas Plenum Temperature of the P2M Instrumented Fuel Rodlets on the Basis of a Thermal-Hydraulic Study of the Belgian Reactor 2 Pressurized Water Capsule

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The authors hereby declare that properties of metallic uranium and hafnium were considered in the initial study instead of the ones related to uranium dioxide and hafnium dioxide, leading to underestimations in the fuel temperature calculation and thus in the temperature gradient applied to the gas plenum. The simulations were corrected considering the right materials and using temperature-dependent properties. As a consequence, a hot point consistently appears at the bottom of the gas plenum, slightly modifying the gas average temperature and behavior. This modification has no impact on the fuel capsule thermal-hydraulic study and does not change the conclusion that the gas located in the plenum can be considered as quasi-static. The authors apologize for this error and propose hereafter:

- The corrected text and Figs. 13 through 16 for Sec. IV.E
- Two corrected sentences and Figs. 18 and 19 for Sec. V.B
- One corrected sentence for Sec. VI

IV.E Behavior of the Gas Located in the Rodlet Plenum

As the main aim of this paper deals with the determination of the gas plenum behavior, this section deals with the study of possible natural convection flow of the gas inside the plenum during irradiation. NEPTUNE_CFD is well suited for the CFD resolution of the gaseous helium behavior in the rodlet plenum. However, the tool does not provide a model for helium (equation of state). Therefore, a perfect gas custom model has been created with the same physical properties as helium. The simulation run in this section thus implies a coupling between NEPTUNE_CFD (water), SYRTHES (solid), and NEPTUNE_CFD (gas). The P2M-Q2 configuration with a maximum LHR of 575 W/cm is chosen for this study, maximizing the thermal gradient between the bottom and the top of the plenum, thus representing the most favorable case for the gas movement inside the plenum. In this configuration, the plenum lower and upper surfaces reach 1556 K and 418 K, respectively. The highest temperature at the bottom of the plenum corresponds to the upper surface of the fuel pellet located at the top of the fuel column. Because of the relatively low temperatures of most of the plenum inner surfaces toward radiative phenomena, radiative heat transfer was not considered in this study for simplification. It is mentioned that this assumption may have led to a slight overestimation of the fuel column upper surface temperature as this hot surface is actually cooled by radiation in the upper direction. However, radiative transfer from the fuel pellet upper surface will be very low compared to the radial conduction transfer in the pellet because the surface subjected to radiation is very small (i.e., circular surface with 1.275-mm diameter at the bottom of the annular Hf pellet). Initially, the plenum is filled with helium at 30 bars.

The first consequence of solving gas plenum behavior is the drop of the time step during the simulation. Because of the gas compressibility, the time step is automatically modified, and the calculation time increases. The gas quickly reaches the plenum boundary temperature, and the natural convection flow of the gas within the plenum is then almost stopped; the gas velocity corresponding to this configuration is illustrated in the paper in Fig. 16a. As the pressure is fixed and remains constant into the cavity, the density adapts itself to satisfy the perfect gas hypothesis, and so, the heavy gas remains located above the light one (gas density increases with the height). The gas temperature is highly influenced by the plenum inner surface temperature, and a radial invariance of the temperature is noticed within the gas; it depends on only the height. A similar simulation has been tested on STAR-CCM+ and gave the same output, confirming both the perfect gas hypothesis and its behavior. Given this unusual behavior of the gas, more detailed theoretical and numerical approaches are confronted in this section to understand and justify the gas dynamic within the plenum.

IV.E.1 Theoretical Approach

The main hypothesis explaining the stratification with a heavy gas on the top and a light one at the bottom is the geometrical restriction, the cylindrical plenum being probably too thin so that the natural convection movement can be initiated given the helium viscosity. The configuration studied here is a variation of the Rayleigh-Bénard instability.[40] Depending on the conditions, buoyancy and gravity can be responsible for the upwelling of the less-dense fluid from the warmer bottom layer, creating a regular pattern of convection cells known as Bénard cells. The Rayleigh-Bénard instability appears only if the gravitational force is dominant compared to the viscous damping one. The balance of these two forces is expressed by a nondimensional parameter called the Rayleigh number defined as

$$R_a = \frac{g\beta\rho C_p \Delta T}{\nu\lambda} L_c^3 \,, \tag{10}$$

where g = gravitational acceleration, β = gas thermal expansion coefficient, ρ = gas density, C_p = gas specific heat capacity, ν = gas kinematic viscosity, λ = gas thermal conductivity, ΔT = temperature gradient in the system, and L_c = characteristic length of the system.

For instance, in the case of a fluid located between two horizontal parallel surfaces with a negative axial temperature gradient, the Rayleigh-Bénard instability is known to occur for Rayleigh number values exceeding a critical value depending on the fluid thermal conductivity, its thickness, and the heat transfer coefficient at the boundary surfaces.[41,42]

Based on the generic Rayleigh-Bénard critical value equal to 1708,[40] this theoretical approach is used to assess the occurrence of natural convection in the P2M-Q2 rodlet plenum at 575 W/cm. Considering a thermal gradient in the system of 1138 K (between the plenum lower and upper surfaces) and the properties of helium[43] at its average temperature (i.e., 987 K), the numerical application of Eq. (10) indicates that Rayleigh-Bénard instability should occur only for characteristic lengths of the gaseous system higher than 6 mm. This result is compared to the ones obtained from numerical simulations in the next section.

IV.E.2 Numerical Approach

Given the complex geometry of the plenum, a complementary study is performed using the real plenum mesh and a simplified one with varying diameters in order to understand the gas flow within the system and to check the theoretical critical length hypothesis. Therefore, a 15-cm-long cylinder filled with helium is considered to match with the P2M-Q2 plenum dimensions. Several diameters between 2 and 10 mm are considered in this parametric study. Initially, the gas is set at 30 bars and 313 K. Temperature boundary conditions are applied to the cylinder according to the P2M-Q2 configuration with a maximum LHR of 575 W/cm, meaning 1556 K and 418 K at the bottom and the top of the plenum, respectively.

As shown in Figs. 13 through 16, the flow structure is modified depending on the plenum diameter. The axial maximum velocity of the gas is very low, around a few millimeters per second, for diameters below 4 mm (Fig. 13). Above 4 mm, the velocity increases up to a maximum value of 0.17 m/s for a 10-mm diameter.

In the case of diameters below 4 mm, a quasi-static state is observed in the majority of the plenum as the gas velocity is very low or null depending on the elevation in the plenum (Figs. 14 and 15). An ~1- to 2-cm-height convection loop takes place at the bottom of the plenum (Figs. 15 and 16) due to the rapid drop of the wall temperature, decreasing from 1556 K to 557 K between the bottom and the top of the upper Hf pellet (see Fig. 3). The gas is heated by the bottom surface and rises at the center of the cylinder. It is then cooled and comes down near the plenum wall (see Fig. 14a).

Conversely, for diameters greater than 6 mm, an ascending flow is created on the outskirt of the domain due to the gas heating at the bottom surface. It is progressively cooled thanks to the decreasing plenum surface temperature until it reaches the top of the plenum, and a descending flow occurs at the center, bringing back the cold gas at the plenum bottom, where it is heated again. The convection in the entire plenum starts above the 6-mm diameter (Figs. 13 through 16), in line with the critical parameter predicted by the theoretical approach and the Rayleigh number. It is interesting to note that it nearly corresponds to the transition from local convection at the plenum bottom to the fully developed convection.

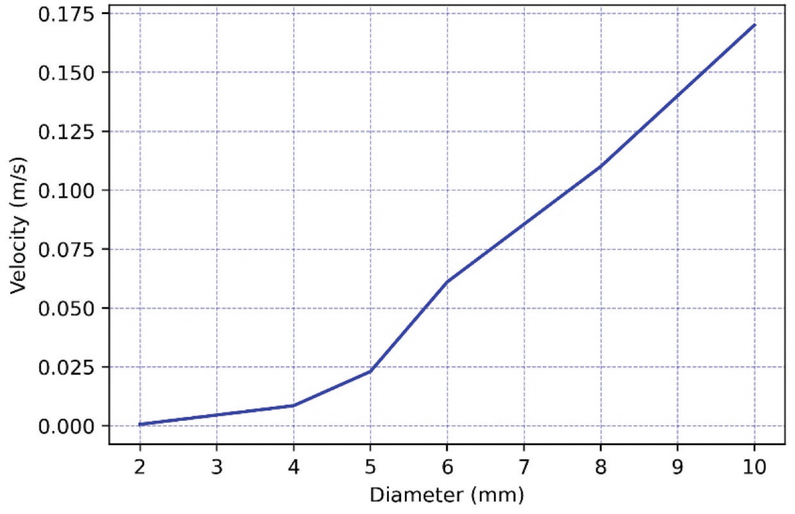

Fig. 13. Simulated gas maximum velocity depending on the plenum diameter.

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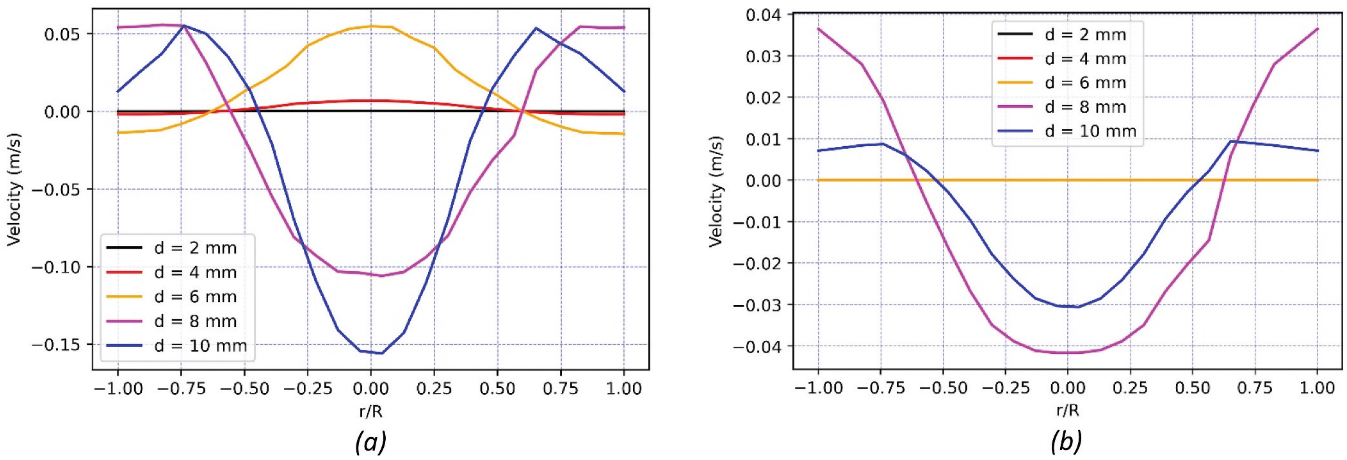

Fig. 14. Radial evolution of the gas velocity for several plenum diameters. Cut at (a) 0.5 cm and (b) 11.25 cm from the bottom of the cylindrical plenum.

The complex geometry of the P2M rods can be seen as an association of cylinders with diameters from 2.55 to 8.6 mm. As shown on Fig. 16a, a tiny convection loop is created in the 2.55-mm-diameter zone at the bottom of the plenum (i.e., at the center of the upper Hf pellet) with an ascending flow at the centerline. It is however negligible as the velocity is on the order of the magnitude of a few millimeters per second. Then, a slight natural convection loop is initiated in the largest zone near the bottom of the plenum (as its width exceeds 6 mm), the flow velocity reaching almost 1 cm/s at its center. The gas is quickly cooled, limiting the loop height to ~1 cm. However, the gas velocity is too low to have a notable impact on the heat transfer, and this region can also be considered as static. Elsewhere, the gas within the plenum is stratified with cold helium on top and hot helium at the bottom because the plenum is too thin to allow movement as the viscous force is stronger than the gravitational force. The gas remains in a steady state even for the maximal LHR corresponding to the P2M-Q2 test at a high LHR, and its temperature varies only along the *z*-axis, imposed by the plenum inner surface.

Considering this result, the CFD simulation of helium is obviously not needed in this study and can be skipped, freeing the time step and gaining simulation time. The gas temperature is simply calculated as the spatial mean of the gas temperature along the *z*-axis. A prospect to these theoretical and numerical approaches is consideration of the fission gas released from the fuel (xenon and krypton) that may impact the natural convection behavior of the gas plenum in relation with their physical properties. This should be the purpose of a future study.

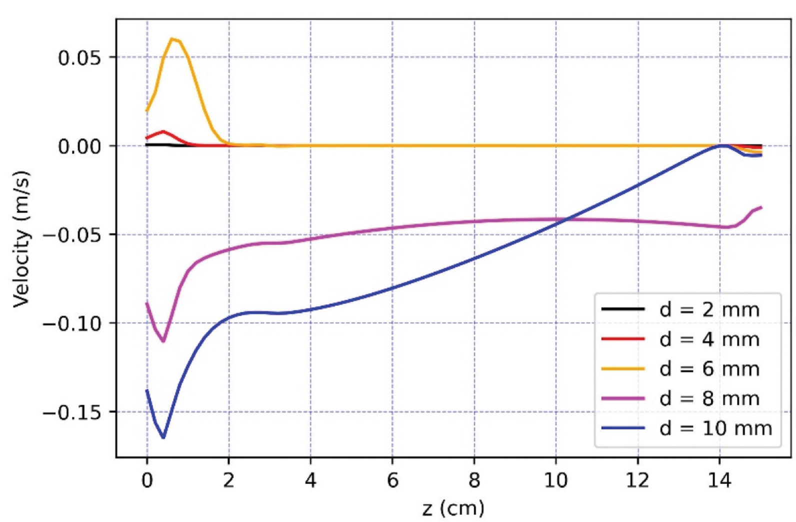

Fig. 15. Axial evolution of the gas velocity at the plenum centerline for several diameters.

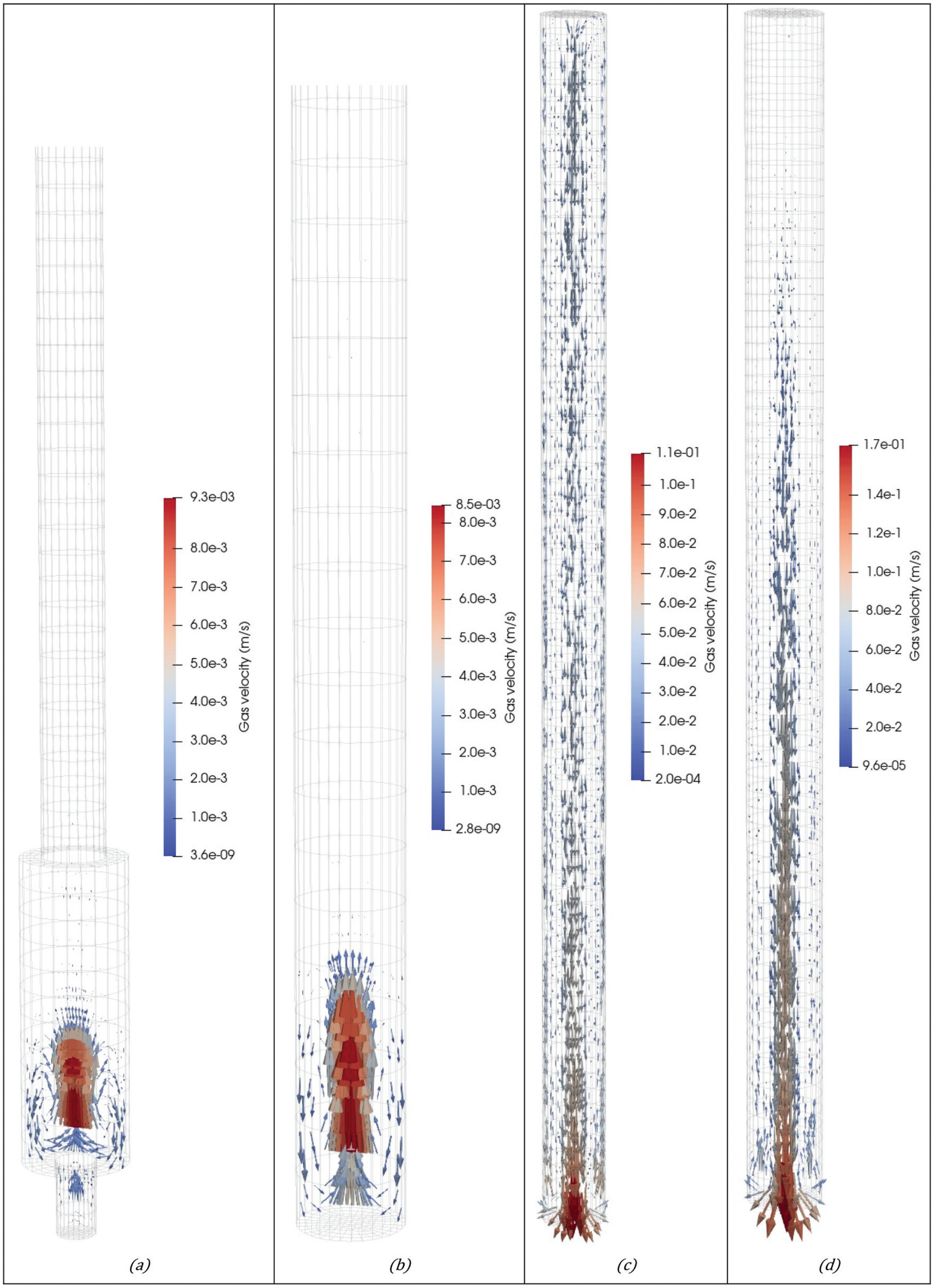

Fig. 16. Visualization of the gas velocity (a) inside the plenum and in the simplified plenum geometry for several diameters: (b) 4 mm, (c) 8 mm, and (d) 10 mm.

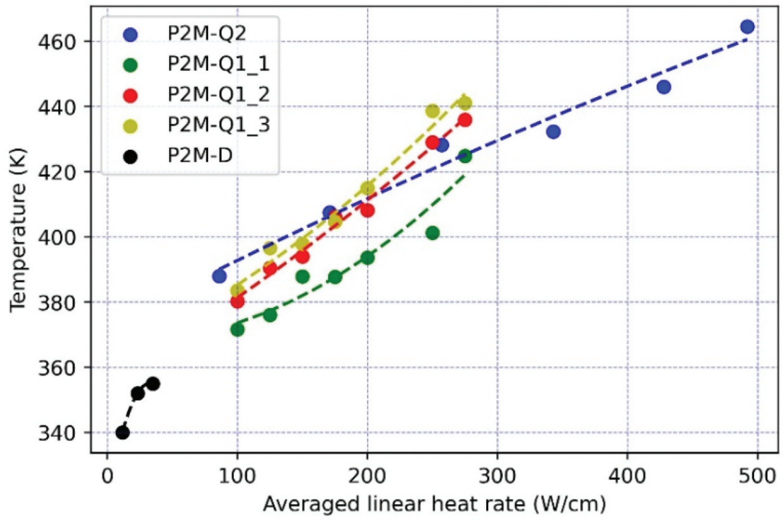

Fig. 18. Evolution of average gas plenum temperature as a function of P2M rodlet average LHR.

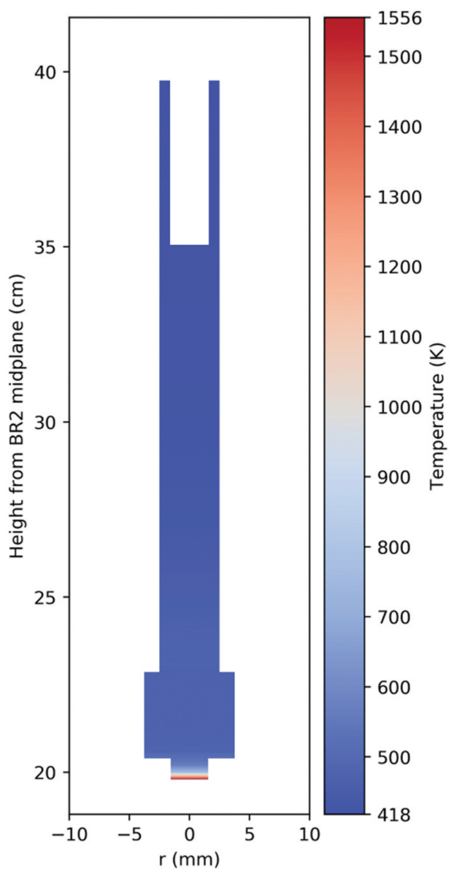

Fig. 19. Cartograph of temperature of the gas plenum of the P2M-Q2 rodlet with a maximum LHR of 575 W/cm.

V.B Determination of the P2M Fuel Rodlet Gas Plenum Temperature

Two sentences in Sec. V.B are edited as follows.

Original text: "However, for a given LHR, whatever the rodlet design or the LHR axial profile shape is, the average gas plenum temperatures differ from less than 20 K."

New text: "However, for a given LHR, whatever the rodlet design or the LHR axial profile shape, the average gas plenum temperatures differ by less than 40 K."

Original text: "As presented in Sec. IV.E, the axial stratification of the gas according to its temperature is a result of the thin diameter of the plenum that does not permit any convection of the fluid in this system."

New text: "As presented in Sec. IV.E, the axial stratification of the gas according to its temperature is a result of the thin diameter of the plenum that does not permit any significant convection of the fluid in this system."

VI. CONCLUSIONS

One sentence in Sec. VI is edited as follows.

Original text: "Indeed, the plenum diameter is too small to permit helium movements by natural convection because in these conditions, the gas has a higher viscous force than its gravitational force."

New text: "Indeed, the plenum diameter is too small to permit any significant helium movement by natural convection, because in these conditions, the gas has a higher viscous force than its gravitational force."