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Reflux Condensation with Various Non-Condensable Gases

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Abstract **–** Reflux condensation experiments were conducted in the PRECISE facility in order to study the effects of non-condensable (NC) gas type (N_2 or He) as well as pressure. The facility is a vertical co-current heat exchanger composed of a closed inner test tube and outer coolant channel. The facility is equipped with instrumentation providing data on vertical and horizontal temperature distributions, operating pressure, liquid film behaviour and wall heat fluxes. The conclusions of these experiments can contribute to the condensation model development in CFD codes and nuclear system safety codes.

Keywords**:** Reflux condensation, non-condensable, vertical tube, gas plugging

1. Introduction

In the last decade studies focused on alternative heat removal capabilities of nuclear systems. During mid-loop operation (shutting down/starting reactor unit) accident scenarios the reflux condensation can be exploited to maintain a safe steady state in a nuclear primary system.

Vierow et al. [1] performed tests on vertical co-current heat exchanger with 19.3 mm inner tube diameter under 1-4 bar operating pressure (OP) and 0.014-0.2 air mass fractions. Empirical correlations were derived for the Nusselt number and condensation heat transfer coefficient where the effect of turbulence was taken into account via the Reynolds number. Steam-air mixture temperature distribution was calculated with these correlations and showed a relatively good agreement with measurements. The heat flux estimation from steam-air mixture was validated by this method however further experimental data was required to cover a wider range of boundary conditions.

Lee et al. [2] conducted experiments with a single U-tube with 16.2 mm inner diameter and 2.8 m height. The operating pressure was 1 bar and the non-condensable (NC) gas was air with mass fraction of 0.02-0.83. The U-tube was placed in a water tank thus natural convection provided cooling. Since test pressures were atmospheric the results could not describe the condensation phenomena adequately for our purposes. In order to address this issue experimental data was compiled with data from Moon's [3] experiments. Comparing measured and calculated heat transfer coefficients with the Nusselt theory a degradation factor was developed as a function of air mass fraction, Reynolds and Jacob number. Analysing the final results one can see that the root mean square error was 27.4 % between experimental and calculated HTC values which was close to the previous 30 % obtained by Moon. Also the maximum test pressure was 2.5 bar which was still low according to industrial standards where reflux condensation appears at 10 bar during SBLOCA tests (ATLAS facility, KAERI). Furthermore, Moon used forced flow on secondary side with high mass fluxes thus it is difficult to compare it with natural convection cooling applied by Lee.

Dehbi et al. [4] chose a different approach using ANSYS CFD Fluent code to integrate a condensation model for vapor-non-condensable mixture medium. Preliminary assumptions were made to simplify modelling, thus the liquid film thermal resistance was neglected and local thermal equilibrium was assumed at liquid-vapor interface. Suction effects which cannot be modelled directly in CFD owing to the imposed non-slip boundary conditions have been incorporated in an ad-hoc fashion through an enhanced diffusion coefficient. Comparison of simulations to experimental data on open flat plate geometries showed relatively good agreement; however, the application of the model to reflux condensation still needs to be validated.

Yi et al. [5] studied the NC effect on steam condensation heat transfer on isothermal vertical aluminum plate under atmospheric pressure. The vapor-air mixture velocity was in a range of 0.1-1 m/s with 5-50 % air mass fraction. Results showed that HTC decreased with plate sub-cooling, their values declined greatly with 5-10 % air mass fractions however when the NC mass fraction exceeded 15 % the impact of NC on condensation rates gradually decreased. The authors explained the tendencies as the heat resistance of the NC layer was relatively stable when air mass fractions were higher. The main part of the effective thermal resistance belonged to the NC layer thus HTC changed slightly when surface sub-cooling increased.

Fu et al. [6] compared CFD (Fluent) calculation results and test data of condensation in a vertical tube (Din=47.5 mm) with steam-air and steam-helium mixtures under 4 bar OP. Centerline thermocouple standard/maximum deviation was 0.25/0.6 °C respectively, Fluent showed good agreement with experimental data. The diffusion coefficient of steam-helium mixture was ~2.5 times higher than that of steam-air under same boundary conditions, thus for forced convection flow mass transfer in steam-helium mixture is larger than in steam-air mixture. The difference is significant when steam inlet molar fraction is small, although condensate rates are similar when steam inlet molar fraction is over 90 %.

Data presented in this paper can provide required information for further model development. Series of experiments were conducted in the PRECISE facility in order to study the effect of pressure and non-condensable gases on condensation. The first considered pure N2 gas load with various mole fractions on 4 bar operating pressure, the second considered the same N2 mole fractions at 5.65 bar OP and the third considered pure He load with the previously used mole fractions at 4 bar OP. Considering safety regulations He was chosen as a substitute of H2 to see how light NC gases behave.

2. PRECISE Facility

2.1. General Features

The facility represents a co-current heat exchanger with a single vertical test tube made of SS2348 alloy. The length and the inner diameter of the test section are 1583x20 mm respectively. In Fig. 1 one can see the layout of PRECISE facility. Coolant enters the at the bottom and provides cooling for steam vapor of the primary side boiled in the heater tank. Demineralized water and the non-condensable gases are supplied from separate tanks which are connected to the test section.

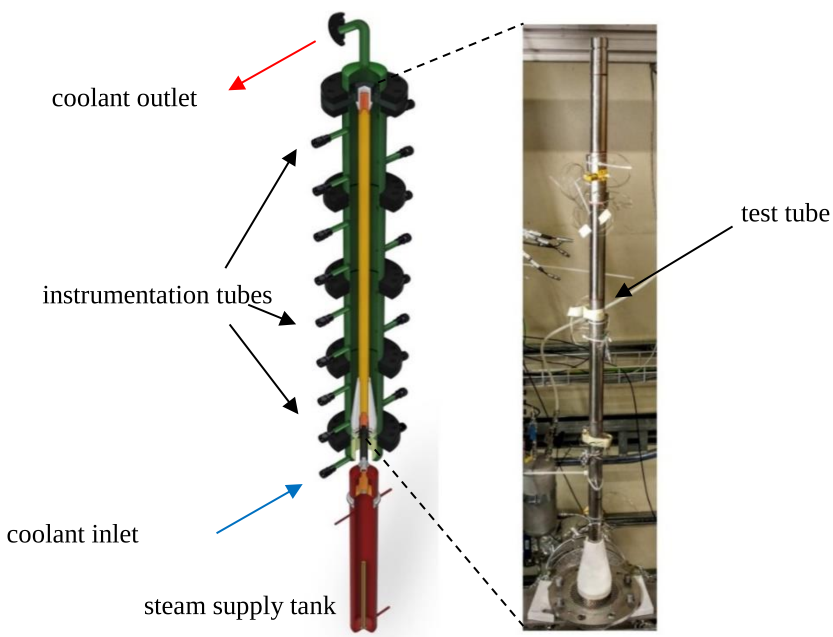

Fig. 1: PRECISE facility layout.

The maximum heater power is 2 kW and the maximum OP is 10 bar. The secondary coolant flow used during experiments was set at 2 m^3/h flow rate to ensure turbulent flow.

2.2. Instrumentation

The test section contains 20 pc. K-type thermocouples (TC), 11 located in the centre of the test tube (on average one TC every100 mm), 8 record inside and outside test tube wall temperatures and one thermocouple is located on the movable probe. High precision pressure transducers are installed in the test section and non-condensable supply tank for well controlled gas injections.

2.3. Operational Procedures

Desired test conditions are set with main parameters as test pressure, NC gas mole fraction, secondary coolant flow rate and desired wall sub-cooling. Based on these values secondary properties are determined such as coolant temperature and pressure. Coolant water can be pressurized up to 10 bars to avoid boiling.

After coolant pre-conditioning step the test section is vacuumed and filled with controlled amount of NC gas mixture and water based on preliminary calculations. Desired test pressure is set and appropriate controls maintain power supply to the main heater as to establish a steady state test conditions.

3. Results

3.1. Nitrogen Tests, 4 Bar OP

First the pure N_2 tests are discussed in this section, the experimental matrix is shown in Table 1. The first case was a reference test with pure steam medium to represent the most efficient reflux condensation conditions. The third column of the table below shows the N_2 mole fraction in the NC gas mixture. Values between 0 and 1 represents a mixture, 0 means the absence of N_2, 1 means pure N_2 gas.

Table 1: Pure N_2 single injection test matrix at 4 bar OP.

Test name	Mole fr NC [-]	N_2 fr in NC mix [%]	Test absolute pressure [bar]	Wall sub-cooling [°C]
NC-MFR-ABS-4_1	0	-	4	20
NC-MFR-ABS-4_2	0.05	1	4	20
NC-MFR-ABS-4_3	0.1	1	4	20
NC-MFR-ABS-4_4	0.15	1	4	20
NC-MFR-ABS-4_5	0.2	1	4	20
NC-MFR-ABS-4_6	0.25	1	4	20

In Fig. 4. the centreline temperature distribution is shown, representing the NC agent effect on vapour temperatures. The highest bulk temperatures can be seen without NC gas; as NC mole fraction increases condensation degrades along the vertical axis. Standard deviations of centreline temperature measurements showed the highest values in the centre of the transition regions, which indicates the most turbulent part of the mixing region. This turbulent zone is the transition between pure water vapour and NC gas plug. Temperature measurements correspond to steam partial pressure assuming thermal equilibrium thus one can divide the test tube into three sections: vapour volume, mixing region and NC-plugged region (see Fig. 2.)

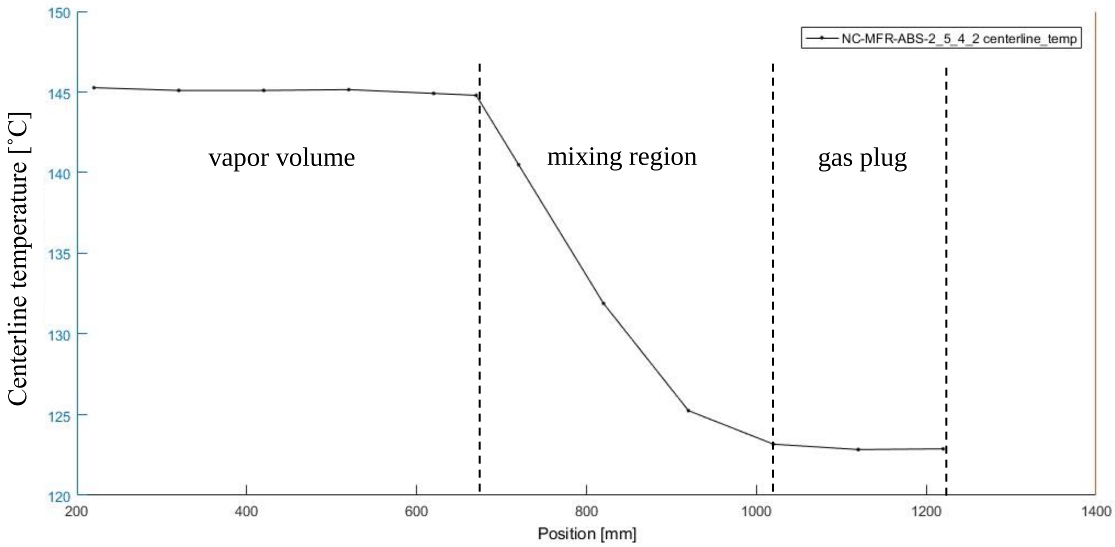

Fig. 2: Test section medium structure.

Considering the TC resolution one can approximate the length of the mixing region with ~400-500 mm. As the gas plug was gradually building up with increasing N2 mole fraction between tests the condensation front descended, finally it could not be observed with even the lowest thermocouple when average N2 mole fraction was higher than 15 %. At this amount of NC gas, calculated steam mass flow dropped by 12.5% compared to pure steam case. This behavior was also seen with pure He tests. It can be explained by the gas plug building up from the tube top. The NC volume covers a bigger part of the tube inner surface in every subsequent test, instead of creating a uniform mixture with water vapor. As the area available to condensation shrinks the heat transfer rates also decrease resulting in lower condensation rates (see Fig. 3.).

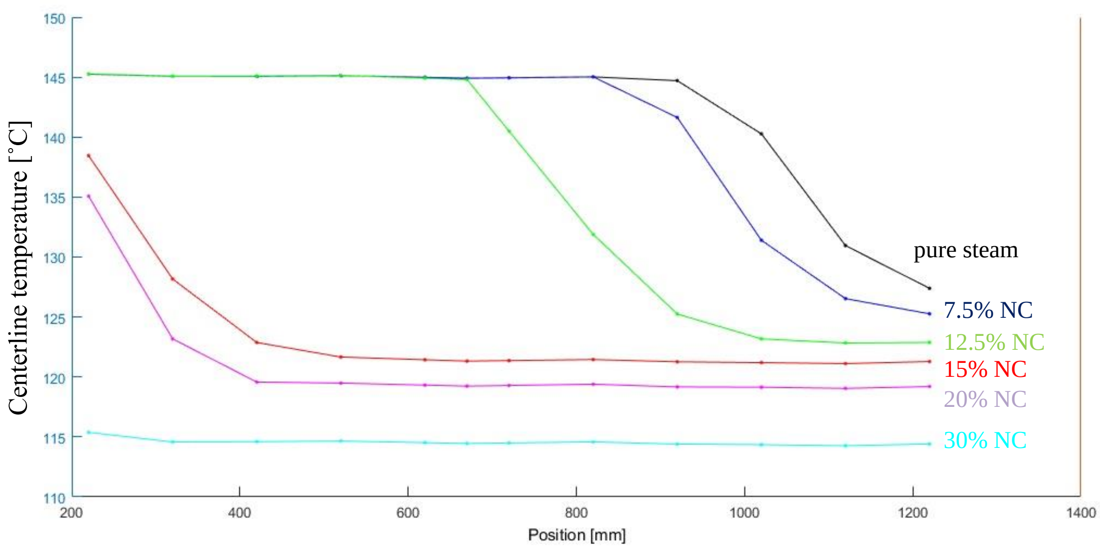

Fig. 3: Centerline temperature distribution of pure N_2 experiments.

Considering the horizontal temperature profiles, one can see that the average temperature drop was ~4°C between the bulk and wall regions is a reasonable value considering wall sub-cooling of 20°C. One can see that the temperature starts to decrease approximately at 2.4 mm from the wall.

3.2. Nitrogen Tests, 5.65 Bar OP

Experiments were conducted with the same N_2 mole fractions at a slightly elevated pressure of 5.65 bar (see Table 2.) to verify the gas plug behavior. Since the heater power was insufficient to maintain a 20°C ΔT at 6 bar OP steady state was maintained at 5.65 bar.

Table 2: Pure N_2 single injection test matrix 5.65 bar OP.

Test name	Mole fr NC [-]	N_2 fr in NC mix [%]	Test pressure [bar]	Wall sub-cooling [°C]
NC-MFR-ABS-N2-6_1	0.05	1	5.65	20
NC-MFR-ABS-N2-6_1_5	0.075	1	5.65	20
NC-MFR-ABS-N2-6_2	0.1	1	5.65	20
NC-MFR-ABS-N2-6_2_5	0.125	1	5.65	20
NC-MFR-ABS-N2-6_3	0.15	1	5.65	20
NC-MFR-ABS-N2-6_3_5	0.175	1	5.65	20
NC-MFR-ABS-N2-6_4	0.2	1	5.65	20

Considering centerline temperature profiles there is no significant difference compared to previous experiments. The shape and the length of the mixing zone remained similar compared to 4 bar OP case, thus the mixing did not change as it is shown in Fig. 4. The thermal BL thickness was approximately 2.2 mm, the temperature difference between bulk and inner wall remained at roughly 5°C.

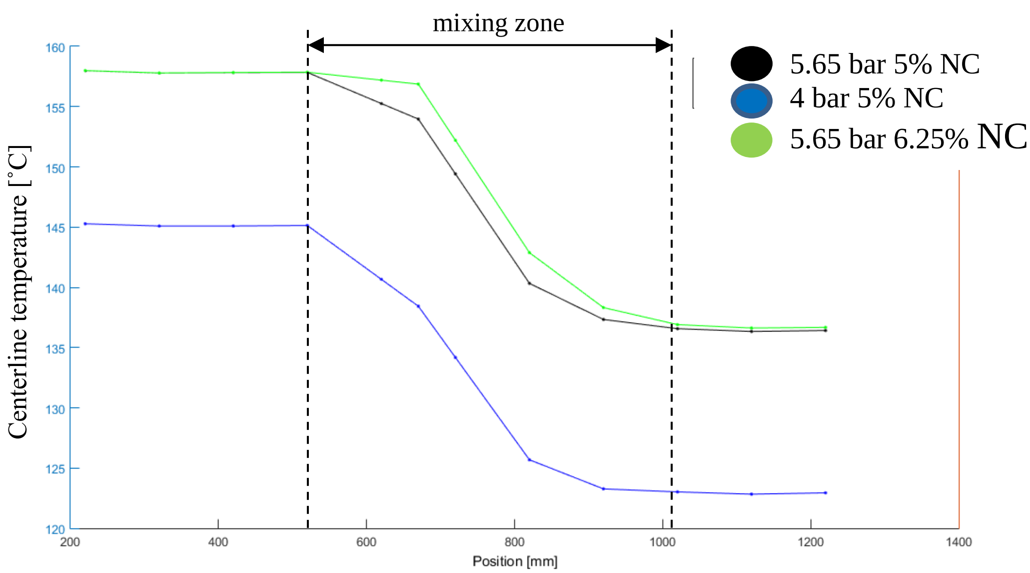

Fig. 4: Temperature distribution of N_2 tests on 4 and 5.65 bar OP.

3.3. Helium Tests, 4 Bar OP

Pure He tests were conducted at 4 bar OP with the same mole fraction range as the N_2 tests. Bulk temperatures showed similar values as before although the mixing zone significantly decreased resulting in a ~300 mm length as can be seen in Fig. 5. Centreline temperature oscillations also showed lower values which can be explained by lower mixing/turbulence due to smaller molecular weight and more severe stratification.

Table 3: Pure He single injection test matrix at 4 bar OP.

Test name	Mole fr NC [-]	N_2 fr in NC mix [%]	Test pressure [bar]	Wall sub-cooling [°C]
NC-MFR-ABS-He-4_1	0.05	0	4	20
NC-MFR-ABS-He-4_1_5	0.075	0	4	20
NC-MFR-ABS-He-4_2	0.1	0	4	20
NC-MFR-ABS-He-4_2_5	0.125	0	4	20
NC-MFR-ABS-He-4_3	0.15	0	4	20
NC-MFR-ABS-He-4_3_5	0.175	0	4	20
NC-MFR-ABS-He-4_4	0.2	0	4	20

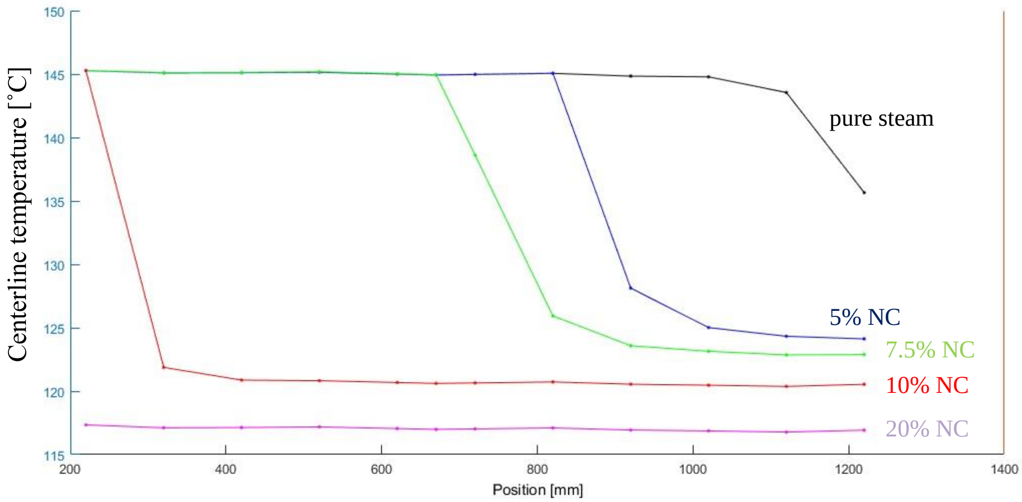

Fig. 5: Temperature distribution during pure He test at 4 bar OP.

Comparing He to N_2 steam mass flows we can see a more effective condensation degradation in case of He. This tendency can be observed in condensation fluxes as well as in temperature distributions. At 12.5 % He mole fraction the condensation is stopped while in case of N_2 it still continues over 15% mole fraction. In Fig. 6 one can see the centerline temperature tendencies with the same amount of N_2 and He at 4 bar OP. The secondary Y axis shows the standard deviations scale; in case of helium the STD values are lower than with nitrogen which indicates the lower level of mixing. Also the length difference of the mixing zones lengths are quite significant – seen as approximately 200 mm.

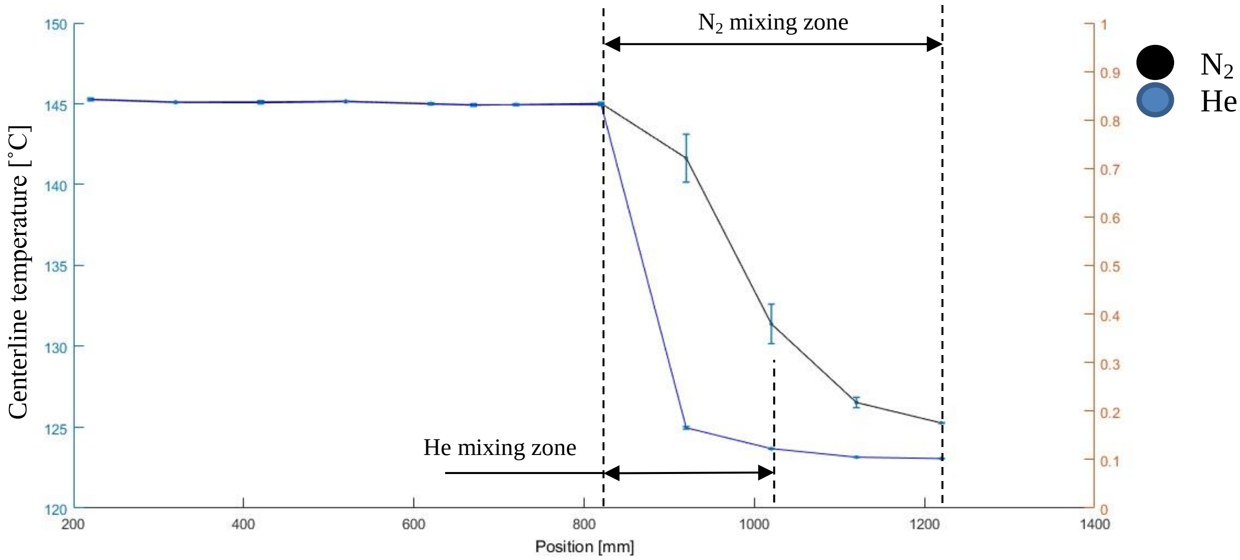

Fig. 6: Centerline temperatures with 7.5% NC mole fraction in case of He and N_2 at 4 bar OP.

The mixing behavior differences can be seen between N_2 and He representing the centerline thermocouple standard deviations. Comparing the same NC mole fraction (7.5%) experiments in Fig. 7. nitrogen shows significantly higher STD values in the elevation of 800-1100 mm where we can see center of the mixing zone in Fig. 6.

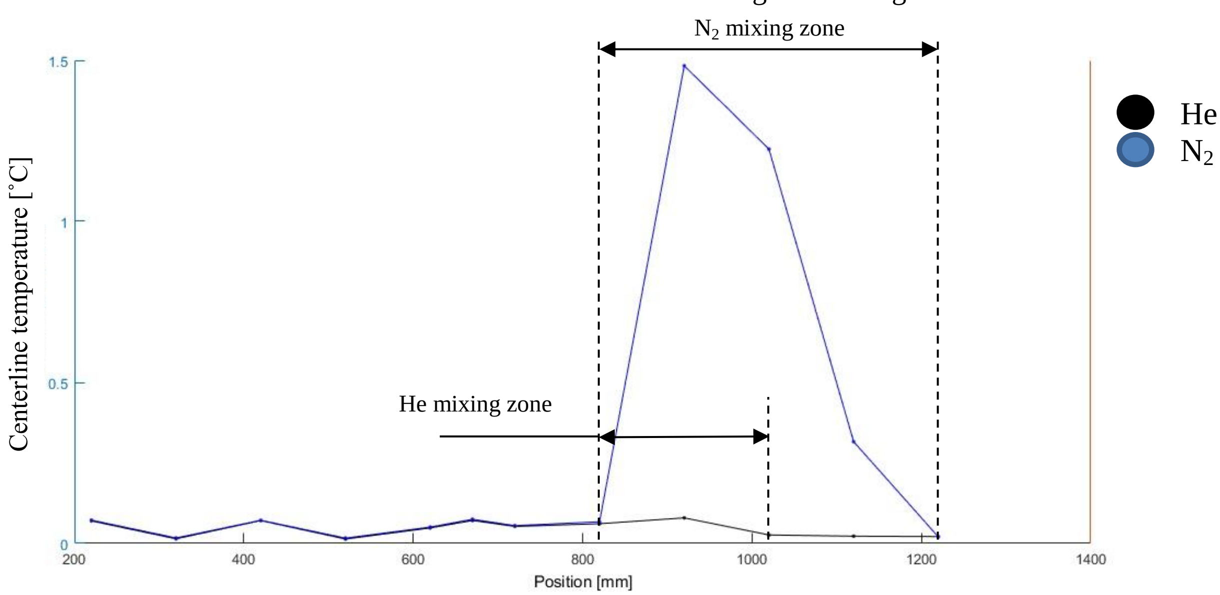

Fig. 7: Centerline temperature STDs with 7.5% NC mole fraction in case of He and N_2 at 4 bar OP.

One can see in steam mass flow decrease in case of He compared to N_2 that He is a more efficient gas in degradation condensation. This effect can be explained by the diffusion coefficient of He which is four times higher than the air (N_2) thus it represents a higher insulation in the wall region than N_2.

4. Conclusion

Successful reflux condensation tests were performed with varying boundary conditions in the presence of NC gases. Pure N2 tests at 4 and 5.65 bar OP showed that the pressure change has no significant effect in the range of 4-5.65 bar on the overall behavior of the gas plug and on the thermal boundary layer although steam flow rates follow the boiling temperature tendencies. Small amounts of NC (15% mole fraction) was enough to significantly degrade condensation in the test tube by covering heat transfer area.

In case of helium tests, one can see that the mixing zone shrunk compared to N2 tests, temperatures showed less deviation with He. Based on recorded steam mass flows, one can conclude that He is a more effective gas in causing condensation degradation than N2. Based on data and molar weights of these NCs it seems that molecule size has a large role in condensation rates; if one extrapolates the observed tendency even lighter hydrogen gas might be an even more hindering gas to condensation.

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