Annex C - Results Numerical Model

belonging to MSc thesis report:
Experimental and numerical analysis of a silica gel packed bed for passive humidity control in museum rooms

by

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Contents

1 | Comparison to experiment by Antonellis

Antonellis has presented the following data measured after cyclic input to a short packed bed:

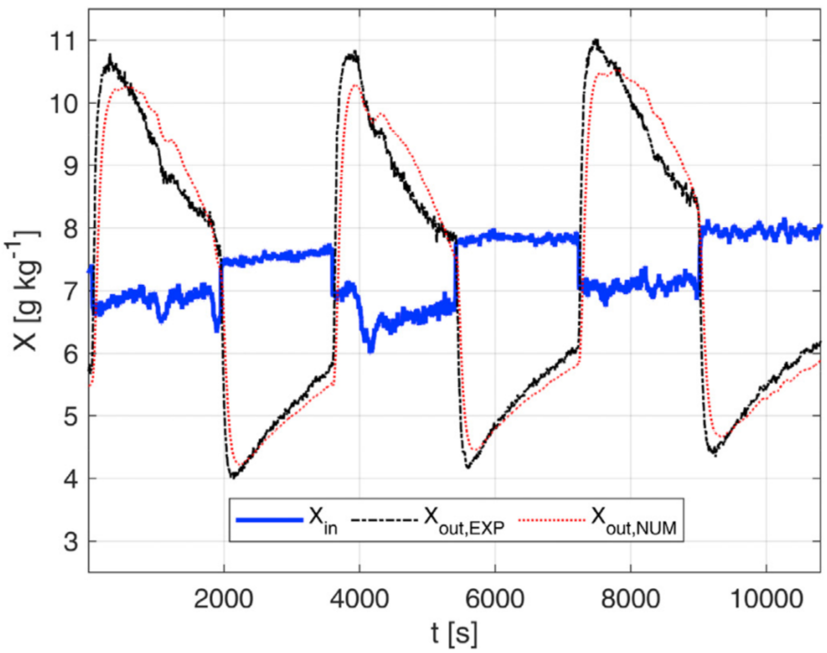


Figure 1.1: Experimental and numerical results for outlet air absolute humidity, after cyclic input to a packed bed, by Antonellis (2019).

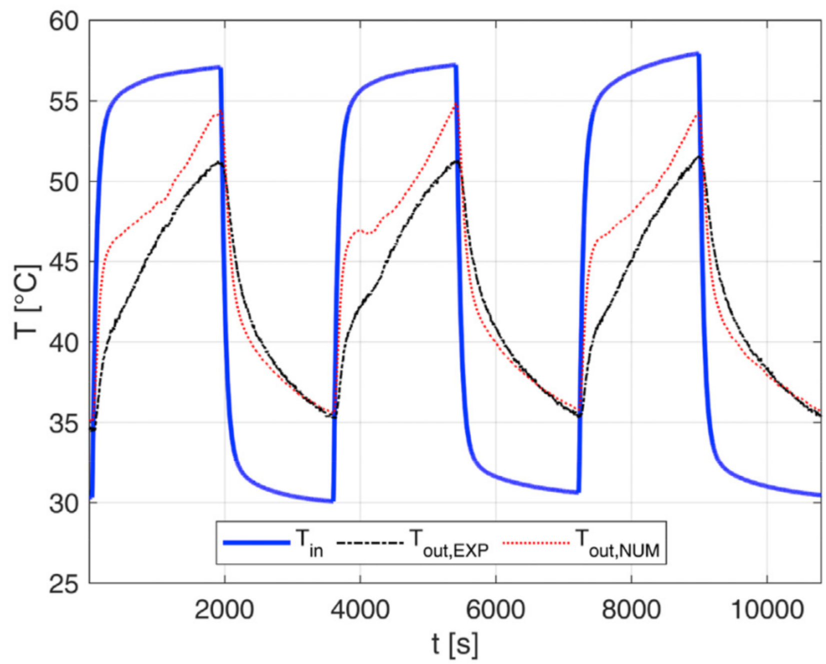


Figure 1.2: Experimental and numerical results for outlet air temperature, after cyclic input to a packed bed, by Antonellis (2019).

The idealized input of Antonellis' experiment is inserted in the PGC model. A summary of the input is given in Table 3.7

D	0.250 m
L	0.055 m
ϵ	0.36
Q	$0.58 * A_{bed}$
n	20
R_p	0.0015 m
$T_{in,1}$	$55.7\ ^oC$
$T_{in,2}$	$32.3\ ^oC$
$m_{in,1}$	0.0070 kg/kg
$m_{in,2}$	0.0079 kg/kg
$T_{0,e}$	$35.0\ ^oC$
$m_{0,e}$	0.0055 kg/kg m

Table 1.1: PGC model input based on Antonellis

Results are shown in Figure 1.3 and 1.4.

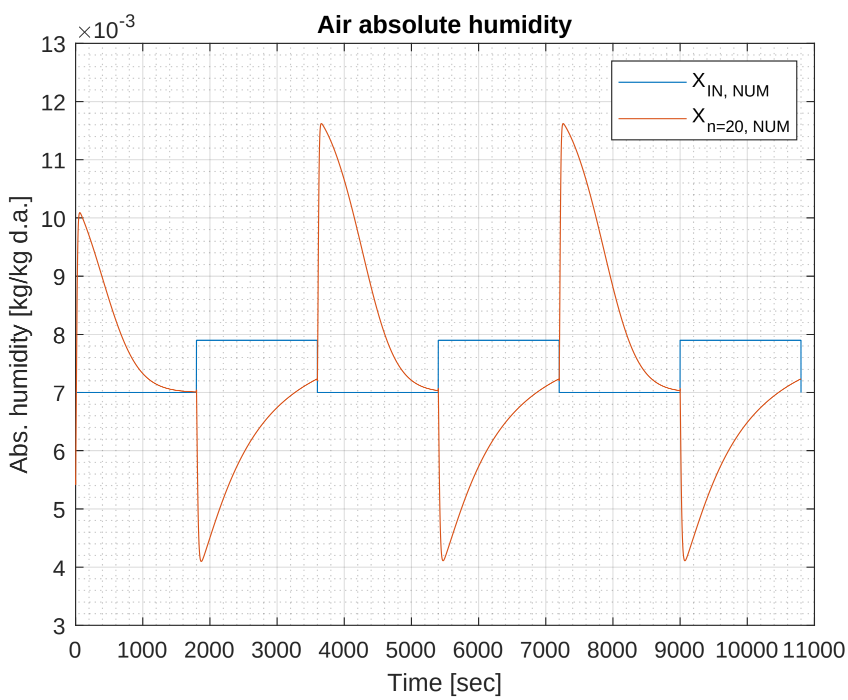


Figure 1.3: Numerical results of PGC model for outlet air absolute humidity, for Antonellis' idealized experimental input

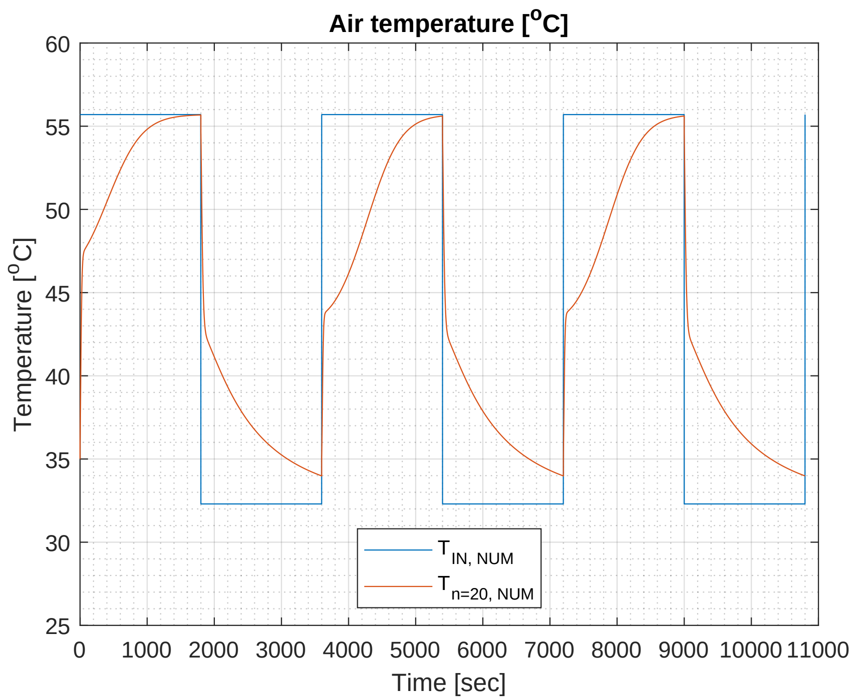


Figure 1.4: Numerical results of PGC model for outlet air temperature, for Antonellis' idealized experimental input

The results are simulated with the values for h_m and h_c obtained from the theoretical study from Pesaran and Mills. In the model result the outlet air reaches input values for both temperature and humidity. In the experimental data this is not the case. This might indicate the mass and heat transfer coefficients h_m and h_c are too high.

Another note to these model results is that the isotherm polynomial from Pesaran and Mills is used, whereas the model from Antonellis uses a different expression of the isotherm, in the form of an exponential function. This was less convenient for integration in the PGC model.

2 | Comparison to experiment by Ramzy and Pesaran

Ramzy has presented a clear overview of single blow sorption experiments executed by Pesaran, as shown in Figure 2.1. Here, d_p is the particle diameter, L the bed length, q_0 the initial silica gel water content, T_{s0} the initial silica gel temperature, v the fluid velocity in the bed, w_{ai} and T_{ai} the absolute humidity and temperature of inlet air.

Table 1
Bed and flow conditions for experiments conducted by Pesaran and Mills [17].

Run	Gel type	Process kind	d_p [mm]	L [cm]	q_0 [kg $_w$/kg $_s$]	T_{s0} [°C]	T_{ai} [°C]	w_{ai} [kg $_v$/kg $_a$]	v [m/s]	t [sec]
1	RD	Des	5.2	5.0	0.26	25.4	25.4	0.0007	0.67	1200
2	RD	Des	5.2	5.0	0.368	25.0	25.0	0.0051	0.4	1800
3	RD	Ads	3.88	7.75	0.0417	23.3	23.3	0.01	0.21	1800
4	RD	Ads	2.54	6.5	0.041	24.7	24.7	0.0106	0.39	1800
5	RD	Des	5.2	5.0	0.37	23.8	23.5	0.009	0.65	1200
6	RD	Ads	5.2	5.0	0.0668	25.6	25.6	0.01093	0.4	1800
7	ID	Ads	3.88	7.75	0.005	24.4	24.4	0.0063	0.67	1200
8	ID	Ads	3.88	7.75	0.0088	23.7	23.7	0.0097	0.45	1200

Figure 2.1: Experiment parameters for single blow experiments by Pesaran and Mills, obtained from Ramzy et al (2011).

The PGC model is used for this comparison. The following input is used, based on the table above. As initial condition, the water content is given, instead of relative humidity. Initial relative humidity is calculated in the Matlab script using the isotherm polynomial from Pesaran.

An important note is that different isotherm polynomials are applied for microporous (RD) and macroporous (ID) silica gel. For microporous silica gel, the following polynomial is used:

$$RH(w) = 100 * (0.0078 - 0.05759w + 24.16554w^2 - 124.478w^3 + 204.226w^4) \tag{2.1}$$

For macroporous silica gel, with $w \leq 0.07$, the following polynomial applies:

$$RH(w) = 100 * (0.000 + 1.235w + 267.99w^2 - 3170.7w^3 + 10087.16w^4) \tag{2.2}$$

D	0.13 [m]
L	$\frac{L}{100}$ [m]
ϵ	0.36 [-]
Q	$v * A_{bed}$ $[m^3/h]$
n	20
R_p	$\frac{d_p}{2000}$ $[m]$
$T_{in,1}$	T_{ai} $[^oC]$
$T_{in,2}$	—
$m_{in,1}$	w_{ai} $[kg/kg]$
$m_{in,2}$	—
$T_{0,e}$	T_{s0} $[^oC]$
$m_{0,e}$	q_0 $[kg/kg]$

Table 2.1: PGC model input based on Ramzy and Pesaran runs from Figure 2.1.

Run 1

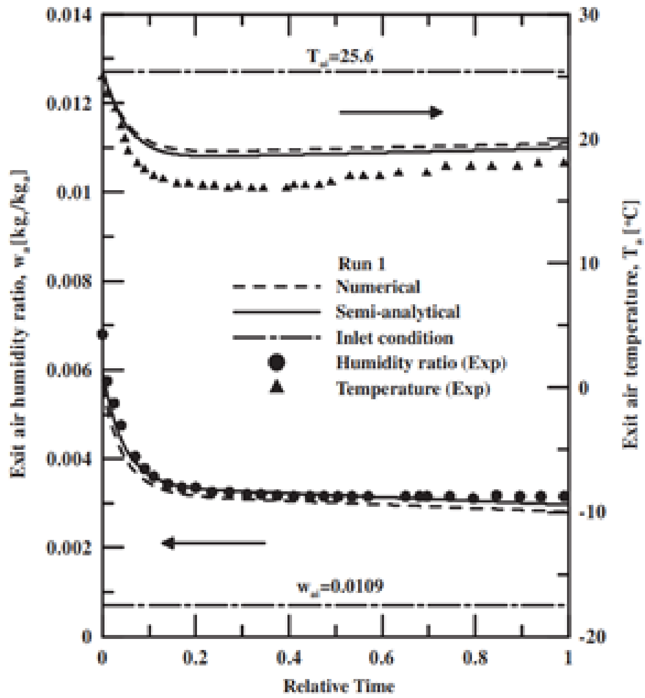
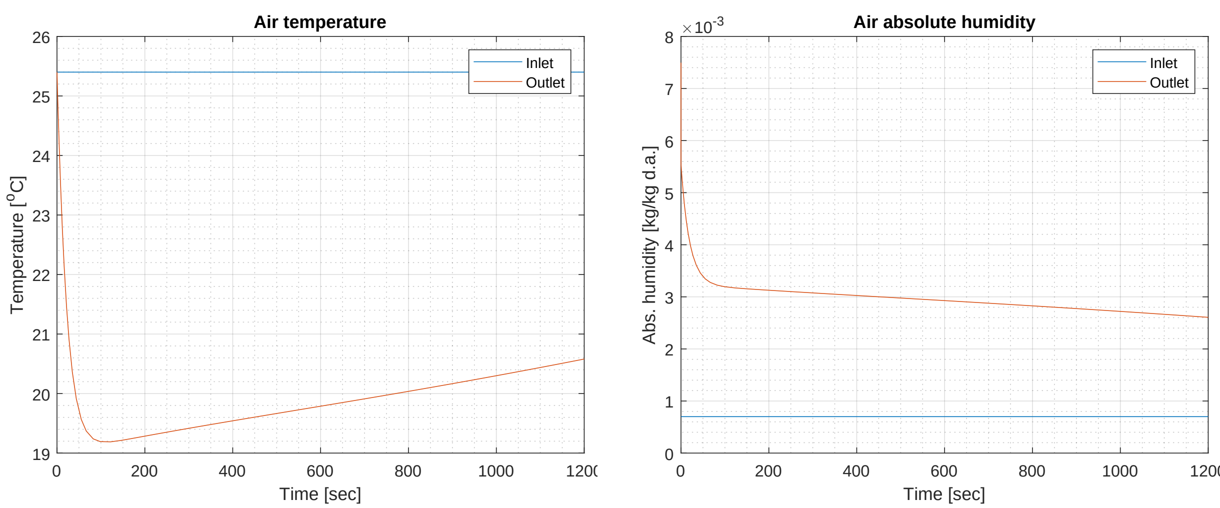


Fig. 9. Comparison of the time history of exit air humidity ratio and temperature for Run (1) obtained using semi-analytical, numerical and experimental techniques.

Figure 2.2: Experimental and numerical results for Run 1, by Ramzy and Pesaran.



(a) (b)

Figure 2.3: PGC model results for (a) air temperature and (b) absolute air humidity.

Run 2

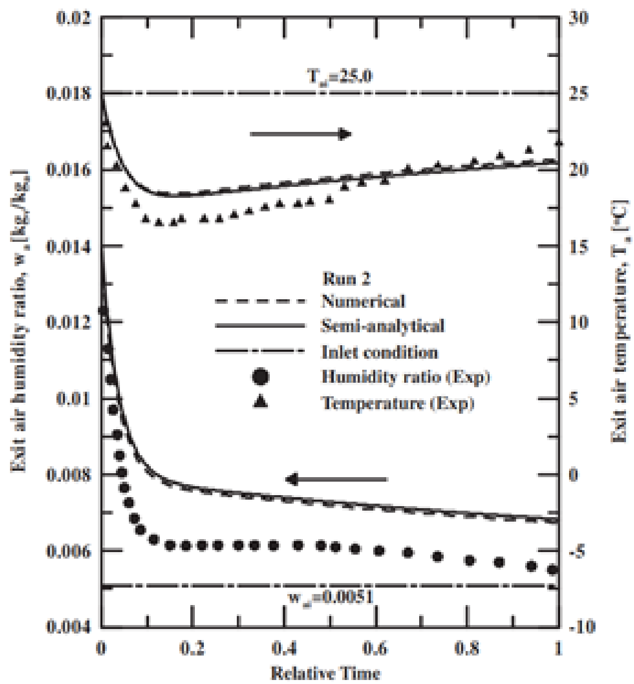
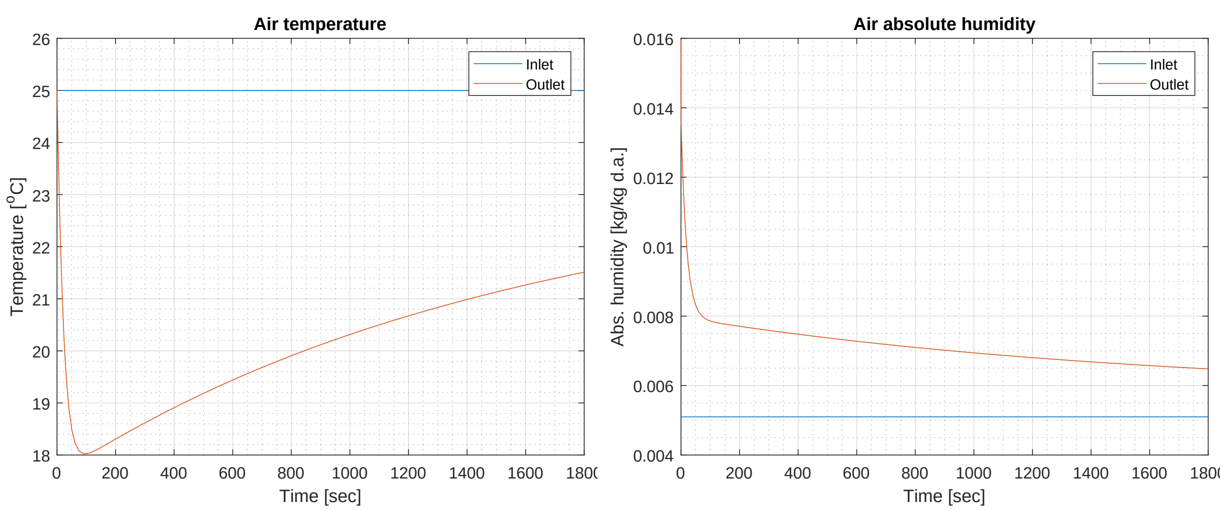


Fig. 10. Comparison of the time history of exit air humidity ratio and temperature for Run (2) obtained using semi-analytical, numerical and experimental techniques.

Figure 2.4: Experimental and numerical results for Run 2, by Ramzy and Pesaran.



(a) (b)

Figure 2.5: PGC model results for (a) air temperature and (b) absolute air humidity.

Run 3

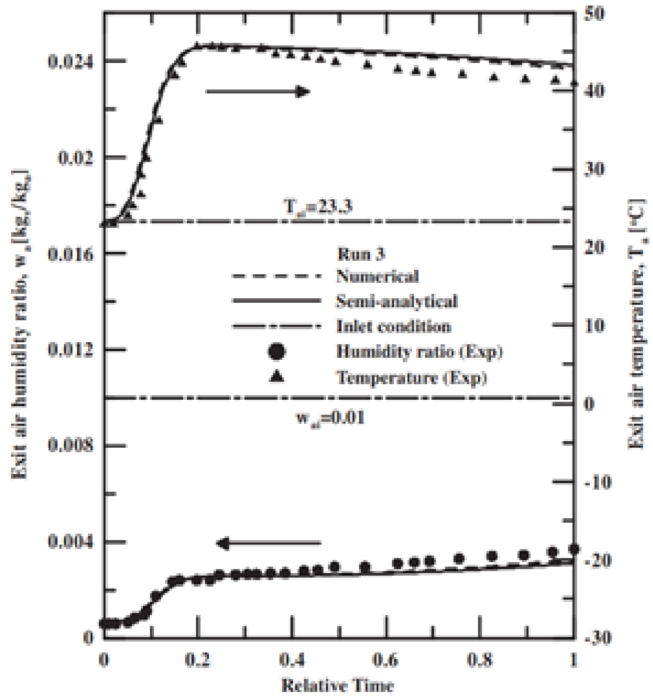
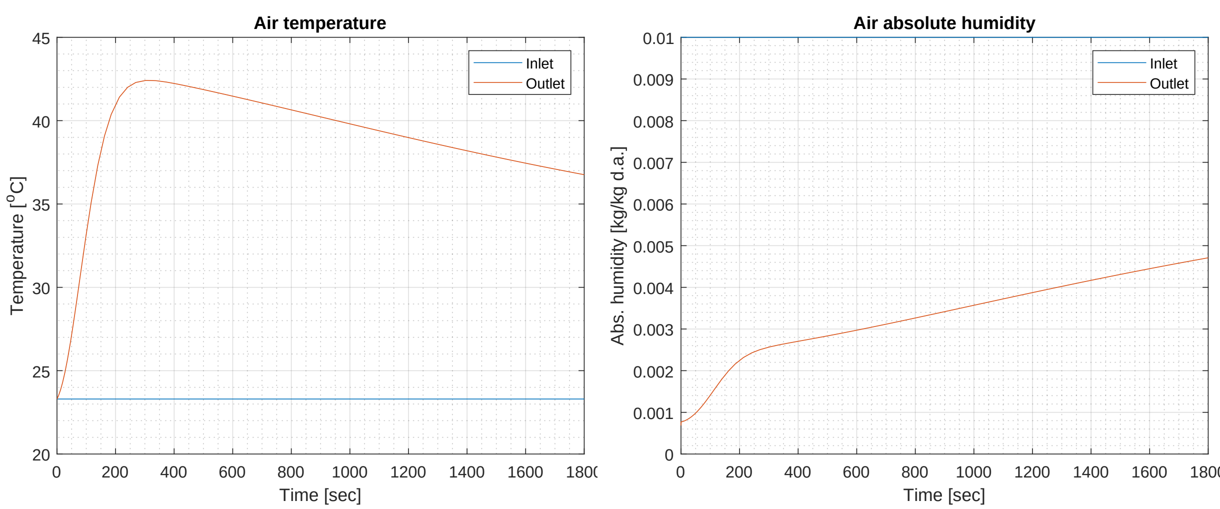


Fig. 4. Comparison of the time history of exit air humidity ratio and temperature for Run (3) obtained using semi-analytical, numerical and experimental procedures.

Figure 2.6: Experimental and numerical results for Run 3, by Ramzy and Pesaran.



(a) (b)

Figure 2.7: PGC model results for (a) air temperature and (b) absolute air humidity.

Run 4

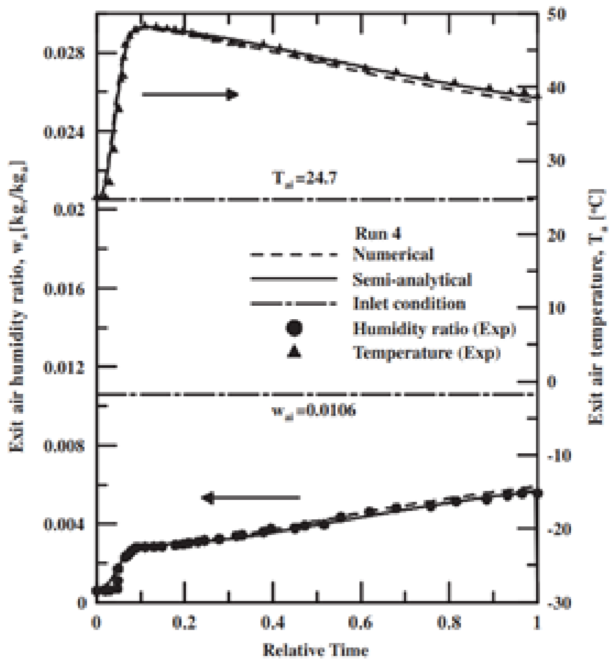
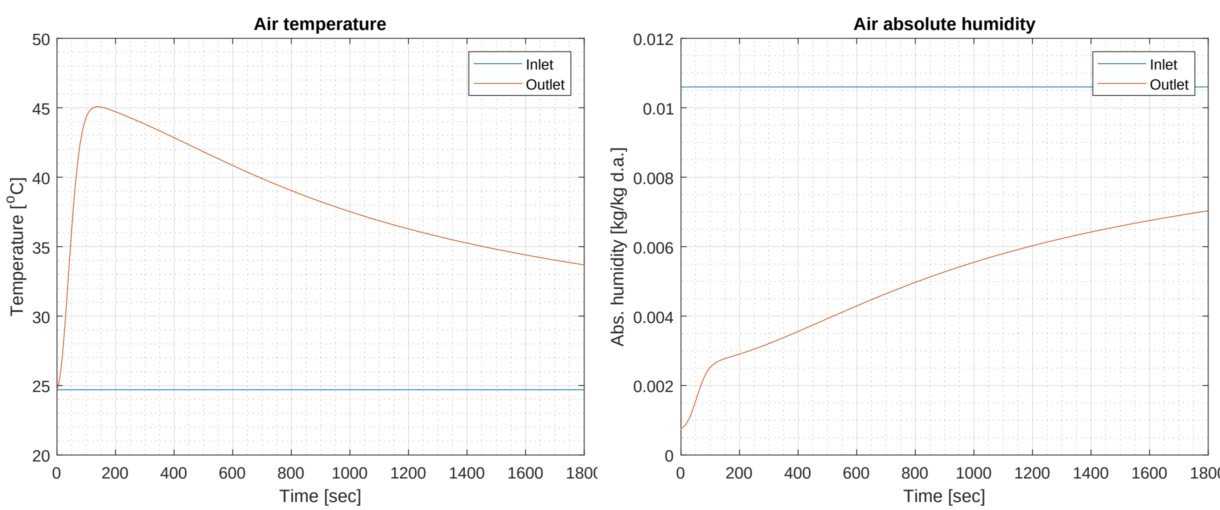


Fig. 5. Comparison of the time history of exit air humidity ratio and temperature for Run (4) obtained using semi-analytical, numerical and experimental procedures.

Figure 2.8: Experimental and numerical results for Run 4, by Ramzy and Pesaran.



(a) (b)

Figure 2.9: PGC model results for (a) air temperature and (b) absolute air humidity.

Run 5

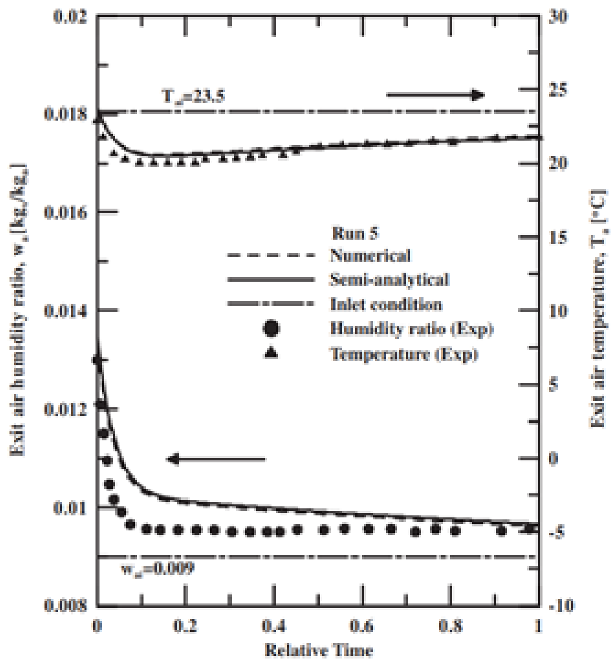
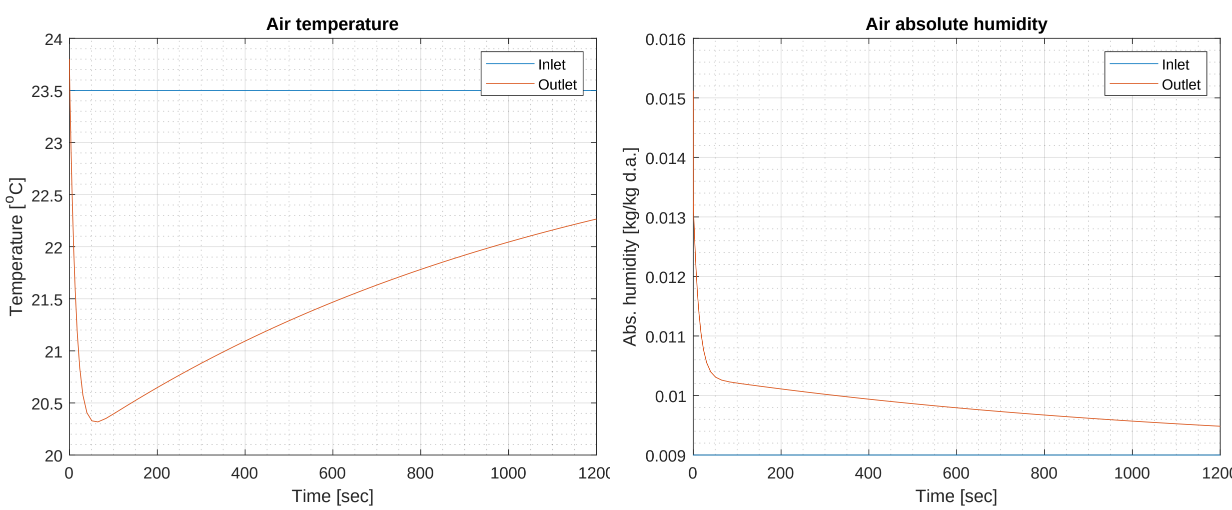


Fig. 11. Comparison of the time history of exit air humidity ratio and temperature for Run (5) obtained using semi-analytical, numerical and experimental techniques.

Figure 2.10: Experimental and numerical results for Run 5, by Ramzy and Pesaran.



(a) (b)

Figure 2.11: PGC model results for (a) air temperature and (b) absolute air humidity.

Run 6

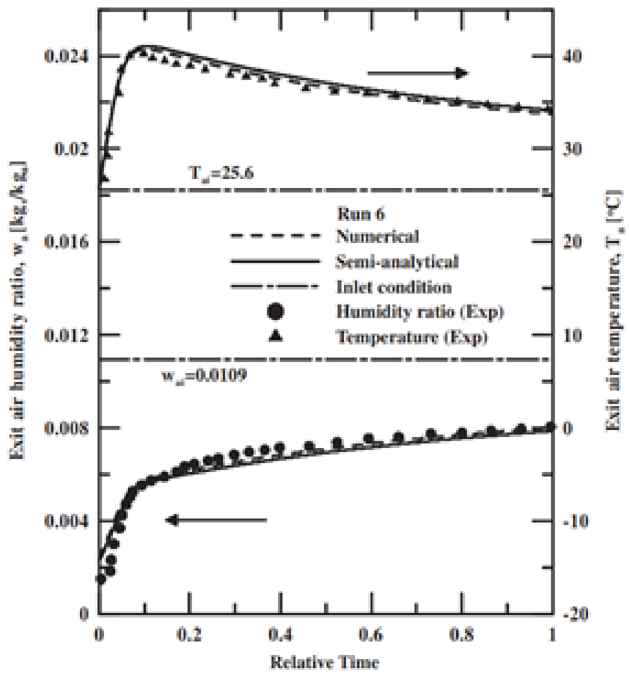


Fig. 6. Comparison of the time history of exit air humidity ratio and temperature for Run (6) obtained using semi-analytical, numerical and experimental procedures.

Figure 2.12: Experimental and numerical results for Run 6, by Ramzy and Pesaran.

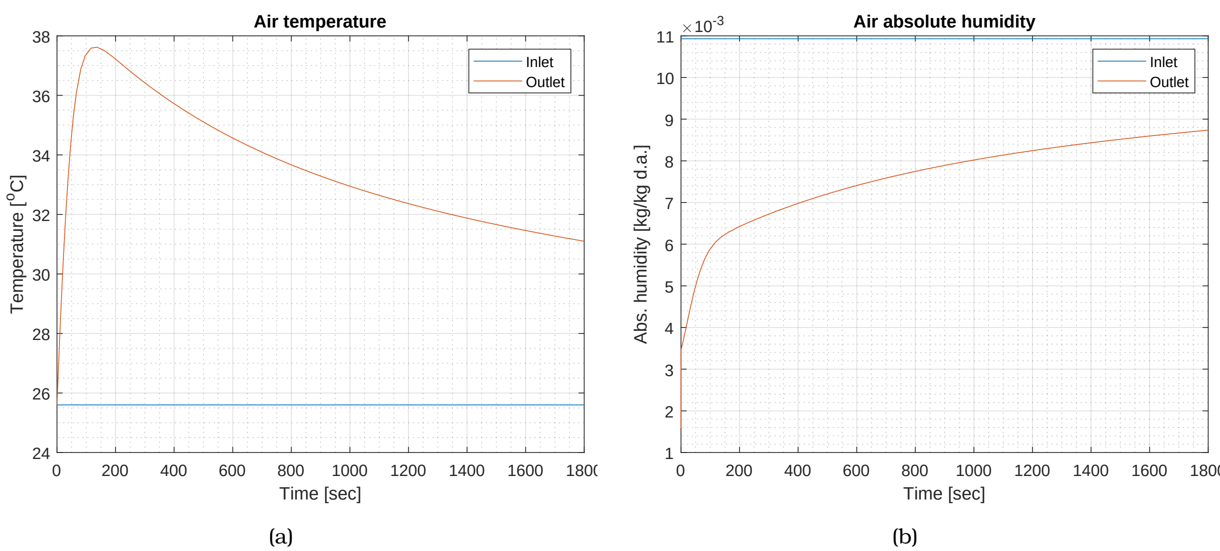


Figure 2.13: PGC model results for (a) air temperature and (b) absolute air humidity.

Run 7

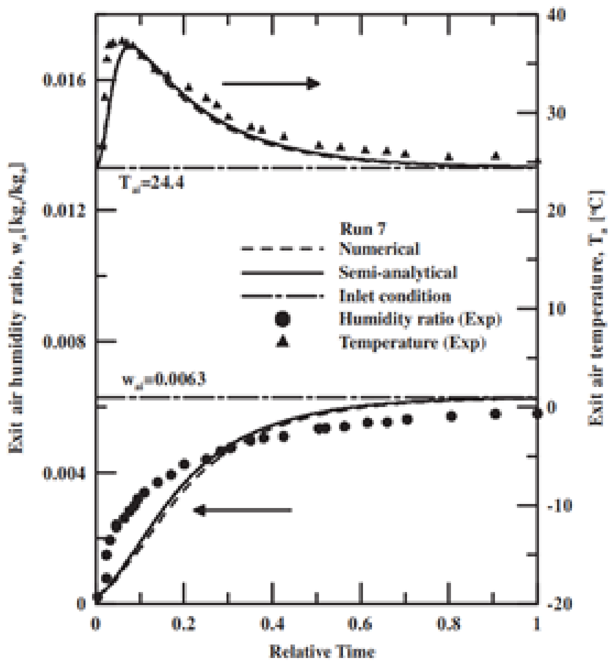
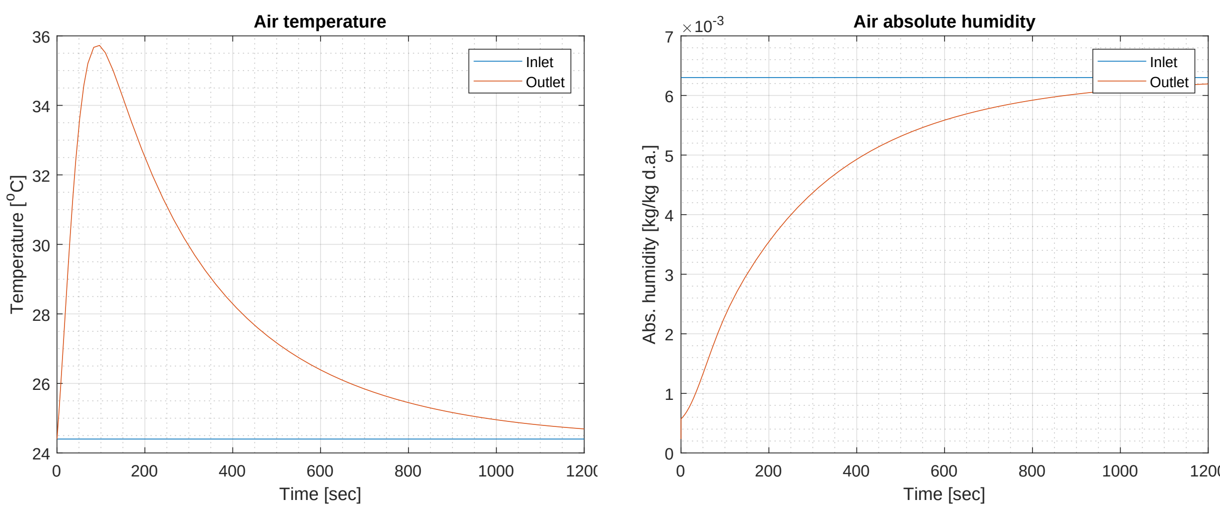


Fig. 7. Comparison of the time history of exit air humidity ratio and temperature for Run (7) obtained using semi-analytical, numerical and experimental procedures.

Figure 2.14: Experimental and numerical results for Run 7, by Ramzy and Pesaran.



(a) (b)

Figure 2.15: PGC model results for (a) air temperature and (b) absolute air humidity.

Run 8

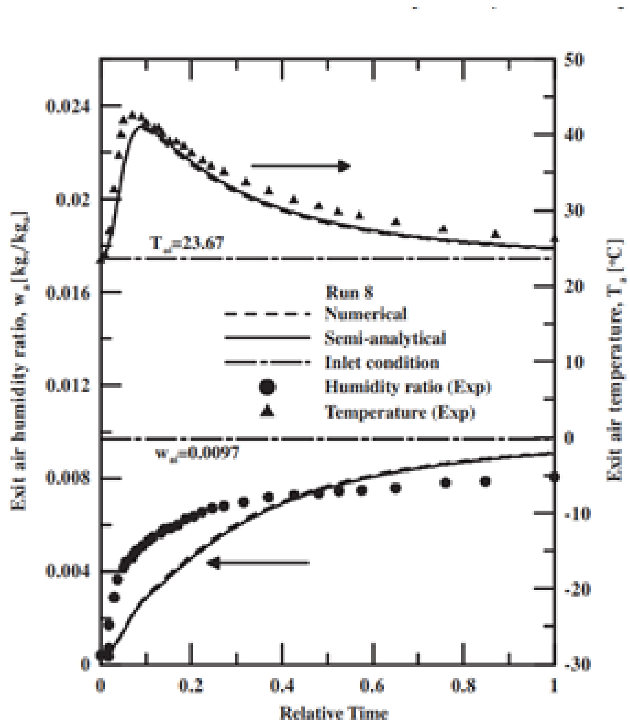
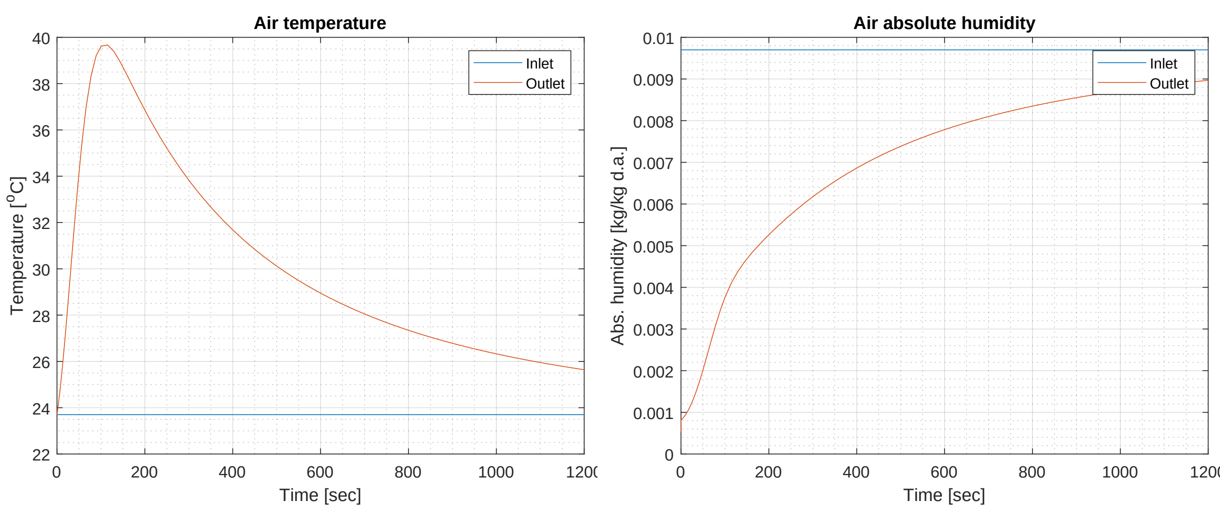


Fig. 8. Comparison of the time history of exit air humidity ratio and temperature for Run (8) obtained using semi-analytical, numerical and experimental procedures.

Figure 2.16: Experimental and numerical results for Run 8, by Ramzy and Pesaran.



(a) (b)

Figure 2.17: PGC model results for (a) air temperature and (b) absolute air humidity.

3 | Comparison to Experiment 2

In this section the experimental conditions from Experiment 2 are inserted in the PGC model. The model results are plotted in one figure together with the experimental results. For every run, three plots are presented: the first plot presents the input and output relative humidity, the second plot presents absolute humidity, and the third plots presents inlet and outlet temperature, both experimental and numerical.

Run 1

Following input parameters are used in the model:

D	0.120 m
L	0.300 m
ϵ	0.36
Q	$1.667e-3\ m^3/s$
n	20
R_p	0.001625 m
$T_{in,1}$	$20.81\ ^oC$
$T_{in,2}$	$20.76\ ^oC$
$m_{in,1}$	0.00937 kg/kg
$m_{in,2}$	0.00595 kg/kg
$T_{0,e}$	$20.80\ ^oC$
$m_{0,e}$	0.00780 kg/kg m

Table 3.1: PGC model input based on Run 1.

Used isotherm polynomial:

$$RH(w) = 1.667 - 33.65w + 265.6w^2 - 845w^3 + 969.9w^4 \tag{3.1}$$

Comparison of RH, X and T at outlet:

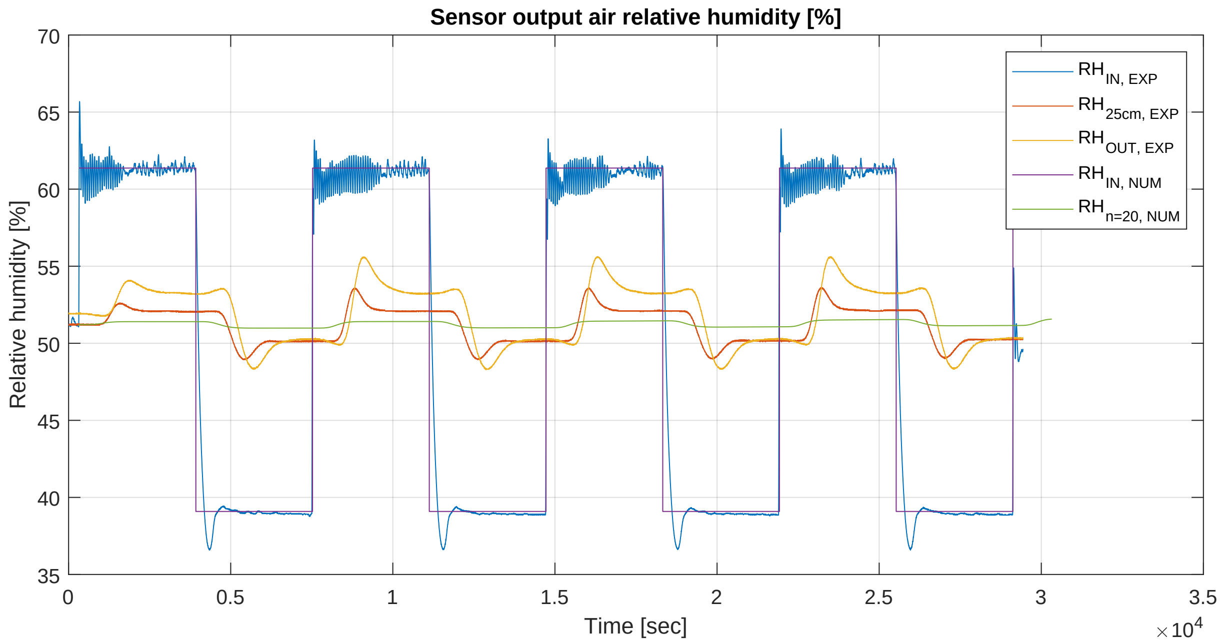


Figure 3.1: Comparison of experimental and numerical results for inlet and outlet relative air humidity.

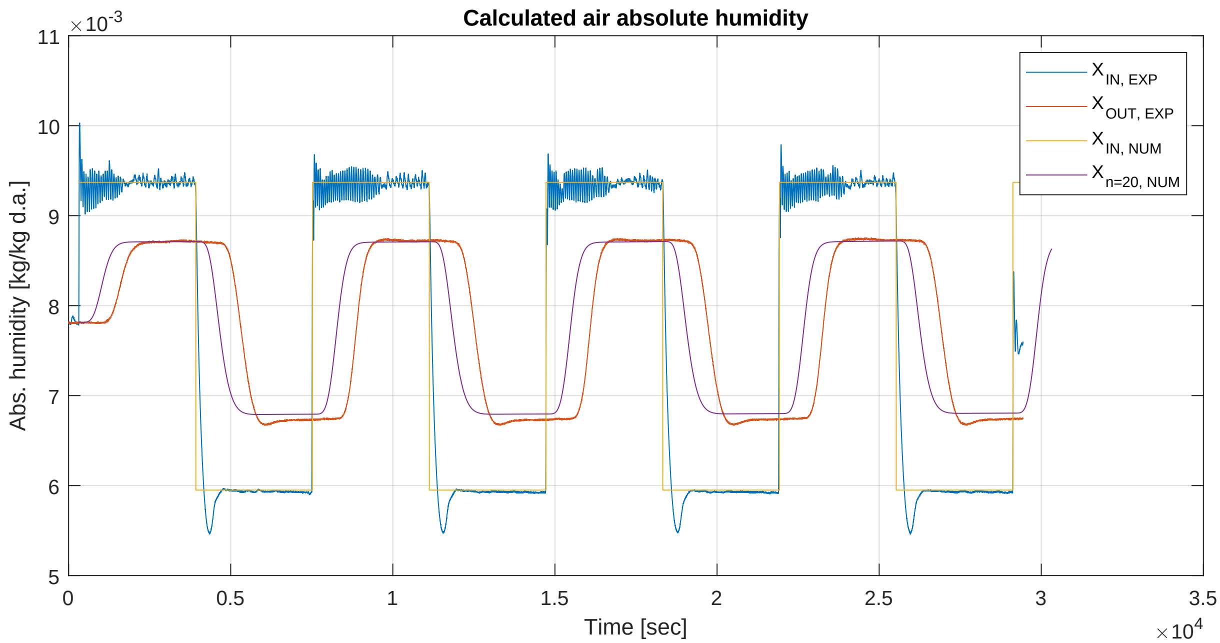


Figure 3.2: Comparison of experimental and numerical results for inlet and outlet absolute air humidity.

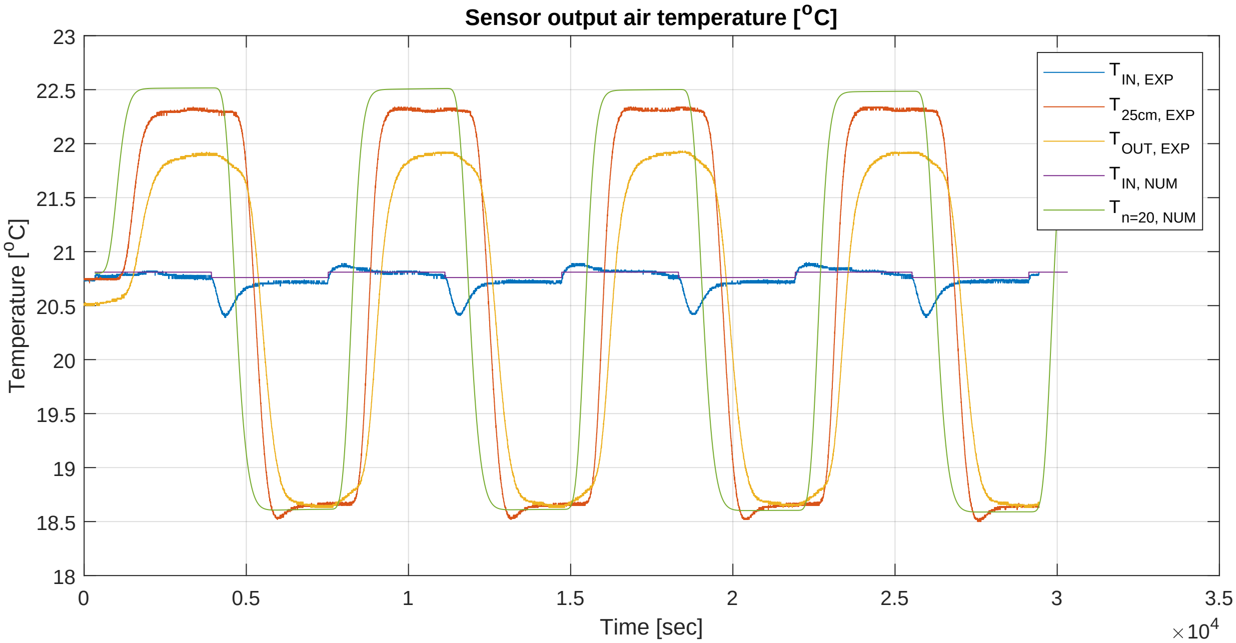


Figure 3.3: Comparison of experimental and numerical results for inlet and outlet air temperature.

Run 2

Following input parameters are used in the model:

D	0.120 m
L	0.310 m
ϵ	0.28
Q	$1.667e-3\ m^3/s$
n	20
R_p	0.001 m
$T_{in,1}$	$21.40\ ^oC$
$T_{in,2}$	$21.38\ ^oC$
$m_{in,1}$	0.00938 kg/kg
$m_{in,2}$	0.00610 kg/kg
$T_{0,e}$	$21.42\ ^oC$
$m_{0,e}$	0.00782 kg/kg m

Table 3.2: PGC model input based on Run 2.

Used isotherm polynomial:

$$RH(w) = 0.008263 + 4.145w - 9.279w^2 + 7.938w^3 \tag{3.2}$$

Comparison of RH, X and T at outlet:

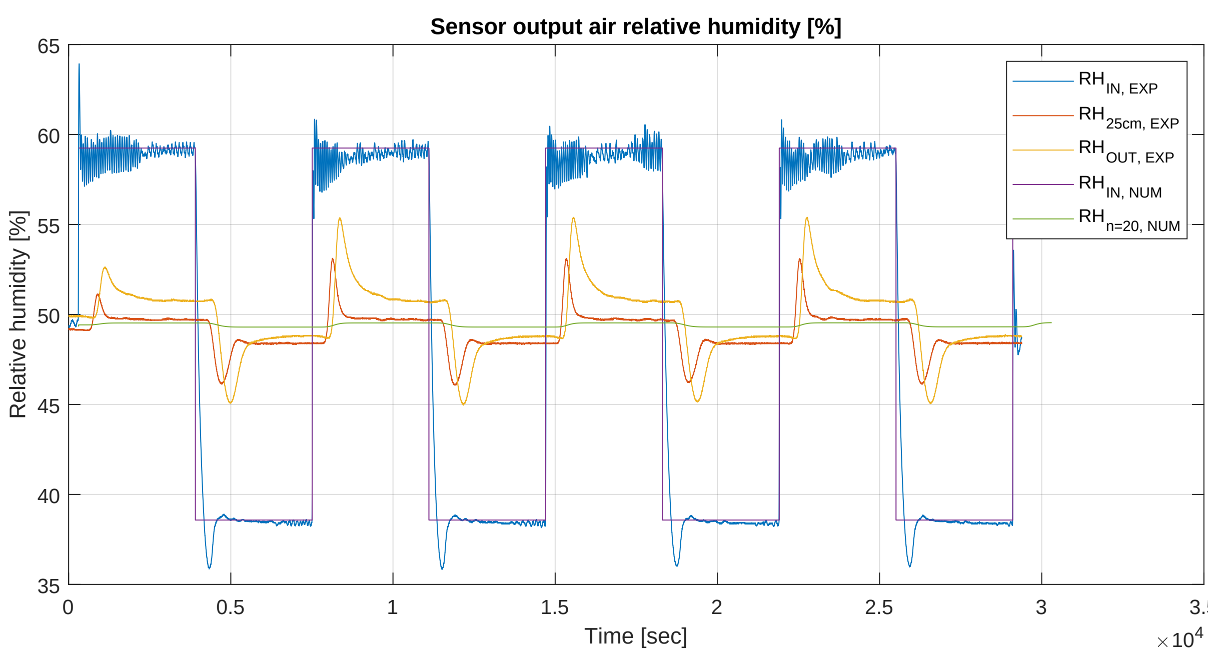


Figure 3.4: Comparison of experimental and numerical results for inlet and outlet relative air humidity.

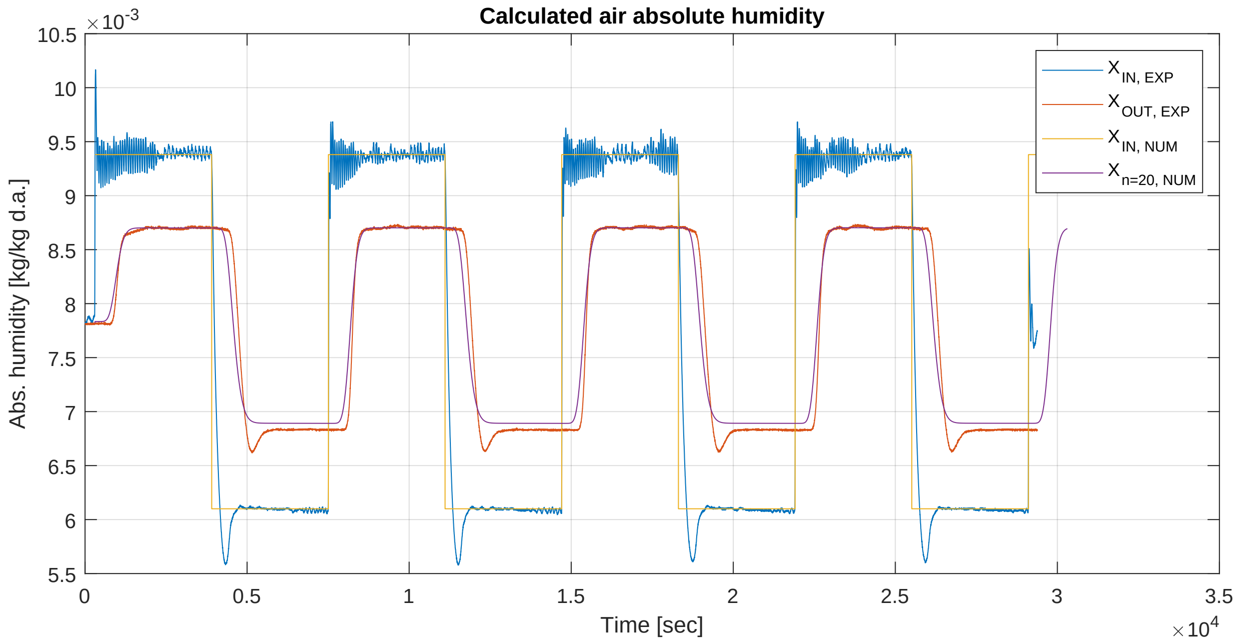


Figure 3.5: Comparison of experimental and numerical results for inlet and outlet absolute air humidity.

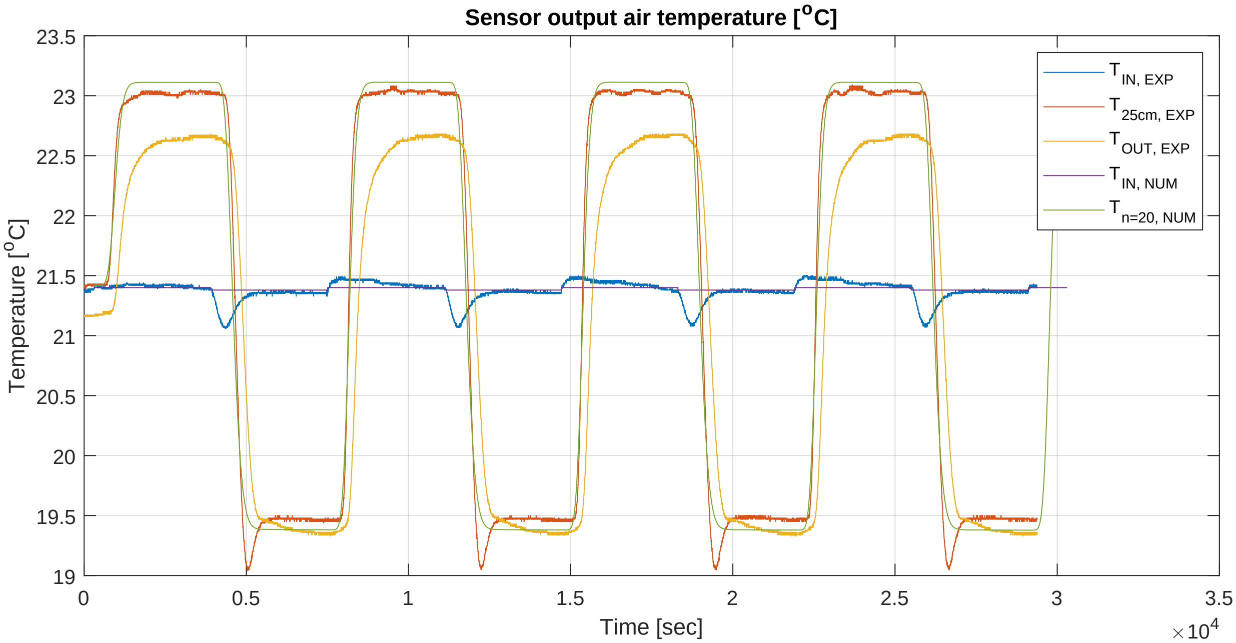


Figure 3.6: Comparison of experimental and numerical results for inlet and outlet air temperature.

Run 3

Following input parameters are used in the model:

D	0.120 m
L	0.300 m
ϵ	0.36
Q	$1.667e-3\ m^3/s$
n	20
R_p	0.002 m
$T_{in,1}$	$22.12\ ^oC$
$T_{in,2}$	$22.08\ ^oC$
$m_{in,1}$	0.01012 kg/kg
$m_{in,2}$	0.00669 kg/kg
$T_{0,e}$	$22.05\ ^oC$
$m_{0,e}$	0.00848 kg/kg m

Table 3.3: PGC model input based on Run 3.

Used isotherm polynomial:

$$RH(w) = 0.782 - 16.74w + 157.4w^2 - 556.8w^3 + 700.1w^4 \tag{3.3}$$

Comparison of RH, X and T at outlet:

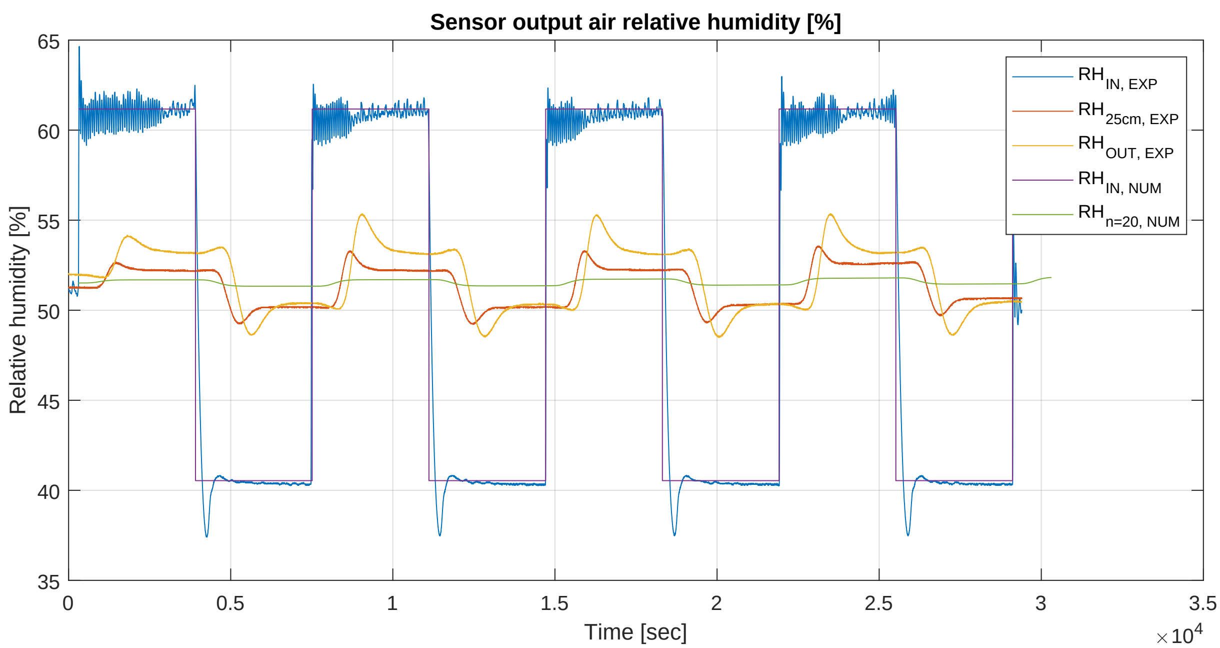


Figure 3.7: Comparison of experimental and numerical results for inlet and outlet relative air humidity.

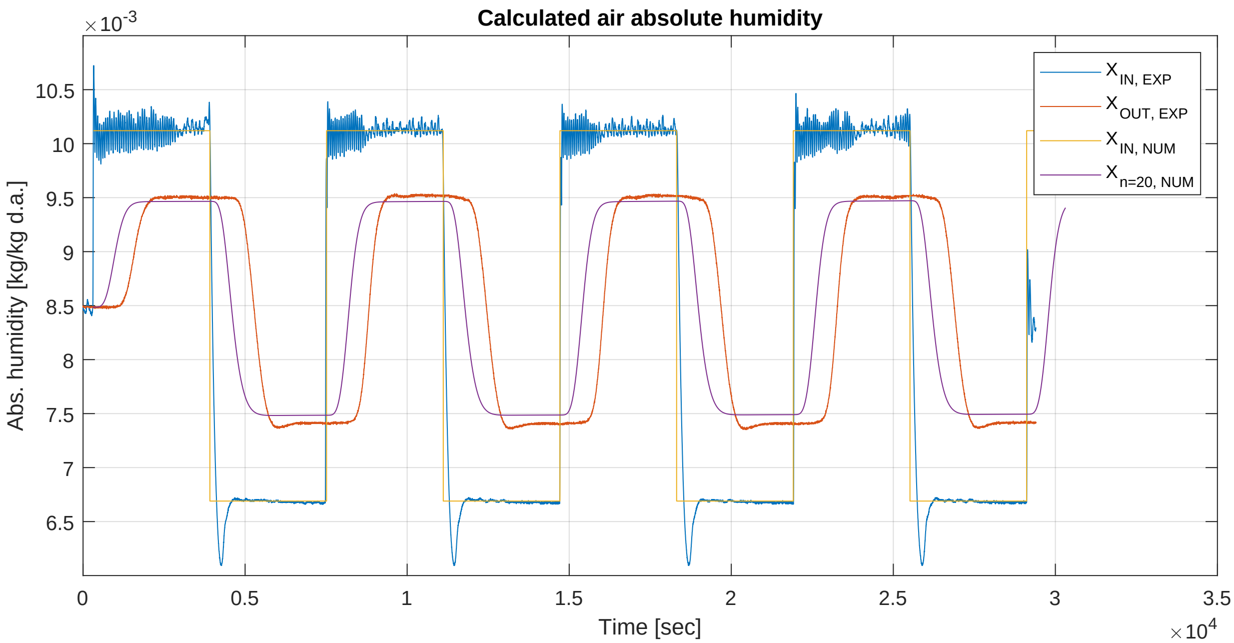


Figure 3.8: Comparison of experimental and numerical results for inlet and outlet absolute air humidity.

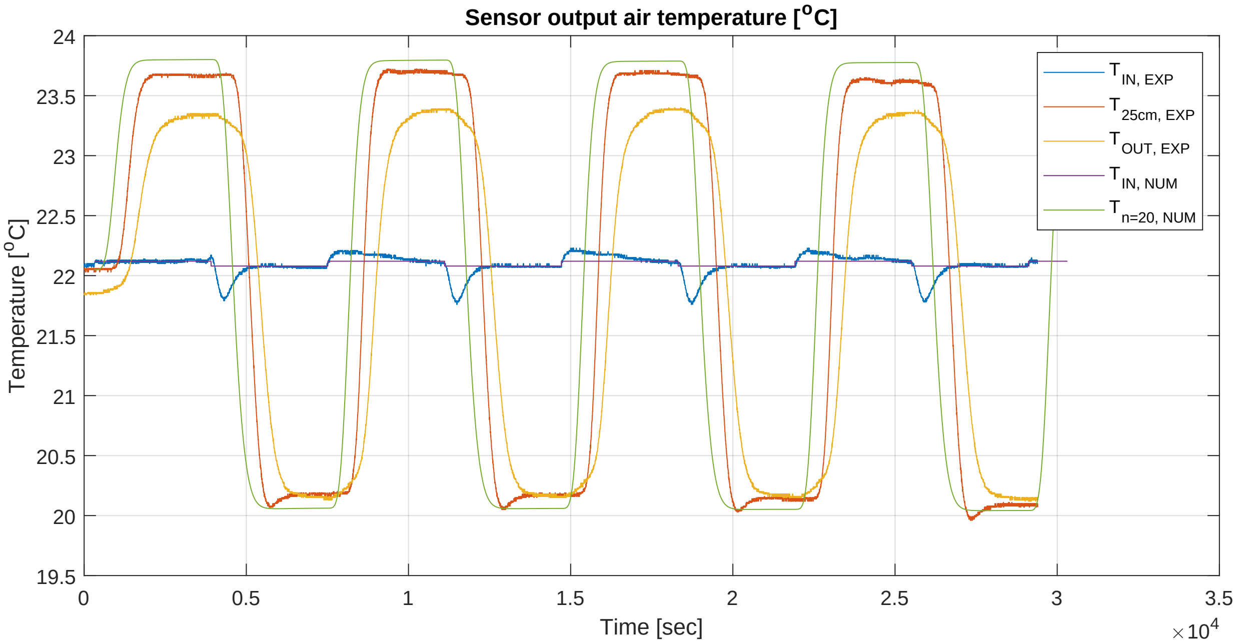


Figure 3.9: Comparison of experimental and numerical results for inlet and outlet air temperature.

Run 4

Following input parameters are used in the model:

D	0.120 m
L	0.310 m
ϵ	0.36
Q	$1.667e-3\ m^3/s$
n	20
R_p	0.002 m
$T_{in,1}$	$22.28\ ^oC$
$T_{in,2}$	$22.15\ ^oC$
$m_{in,1}$	0.01030 kg/kg
$m_{in,2}$	0.00657 kg/kg
$T_{0,e}$	$22.25\ ^oC$
$m_{0,e}$	0.00845 kg/kg m

Table 3.4: PGC model input based on Run 4.

Used isotherm polynomial:

$$RH(w) = 0.005046 - 0.5135w + 19.01w^2 - 80.69w^3 + 97.96w^4 \tag{3.4}$$

Comparison of RH, X and T at outlet:

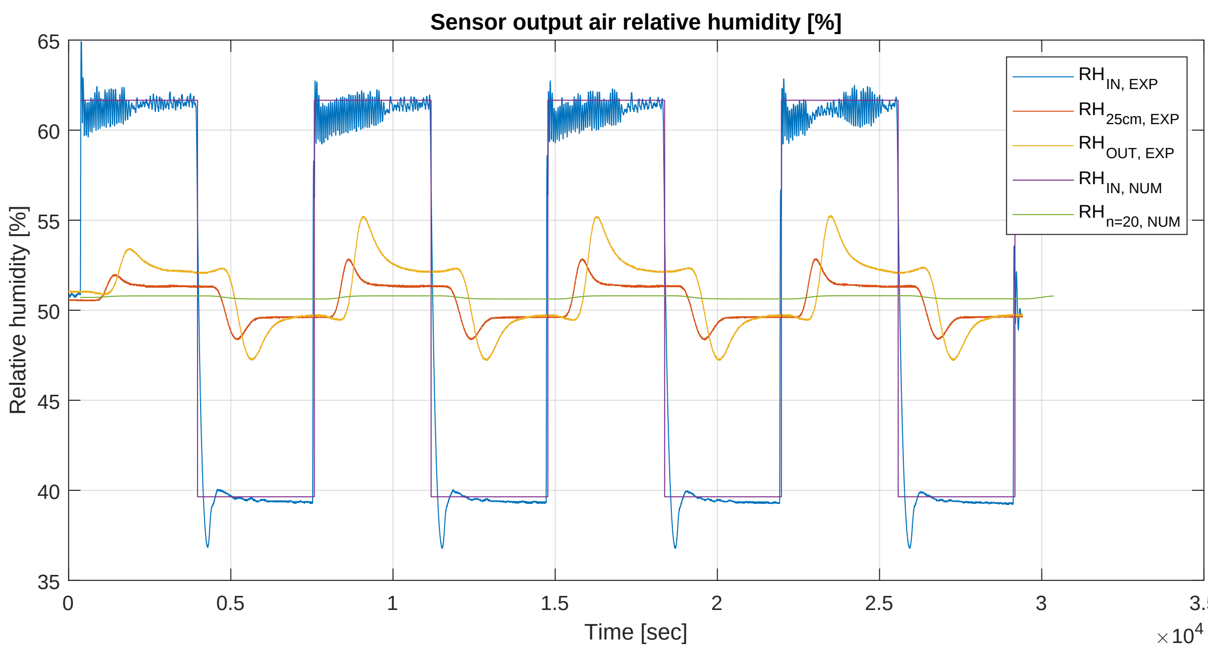


Figure 3.10: Comparison of experimental and numerical results for inlet and outlet relative air humidity.

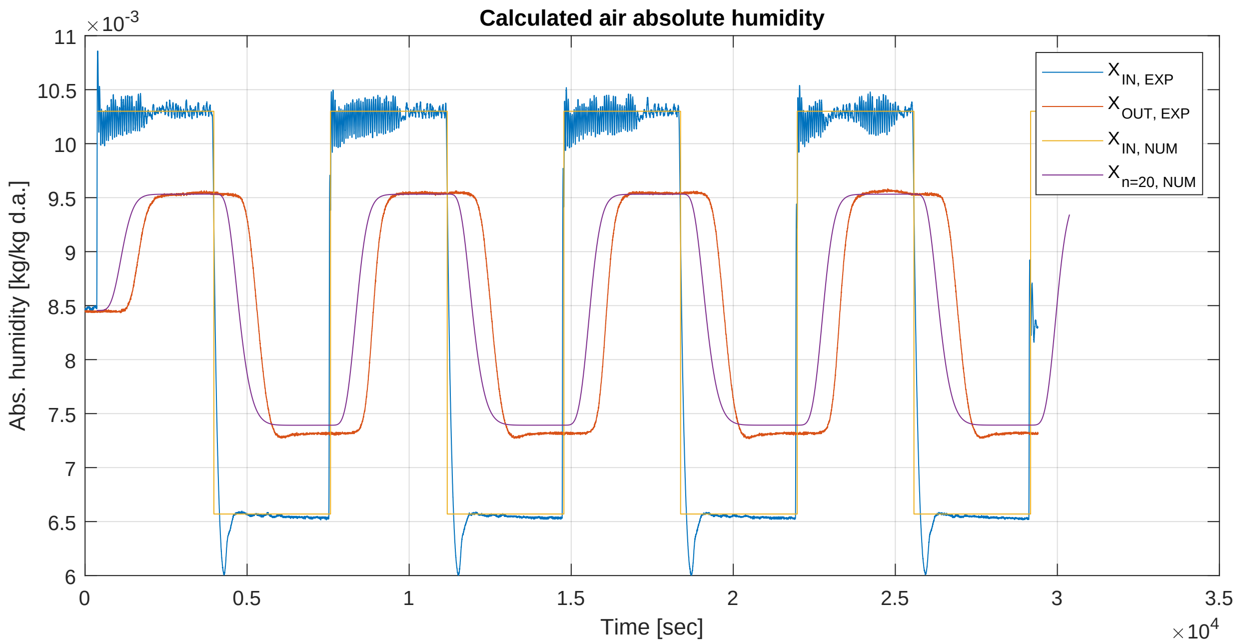


Figure 3.11: Comparison of experimental and numerical results for inlet and outlet absolute air humidity.

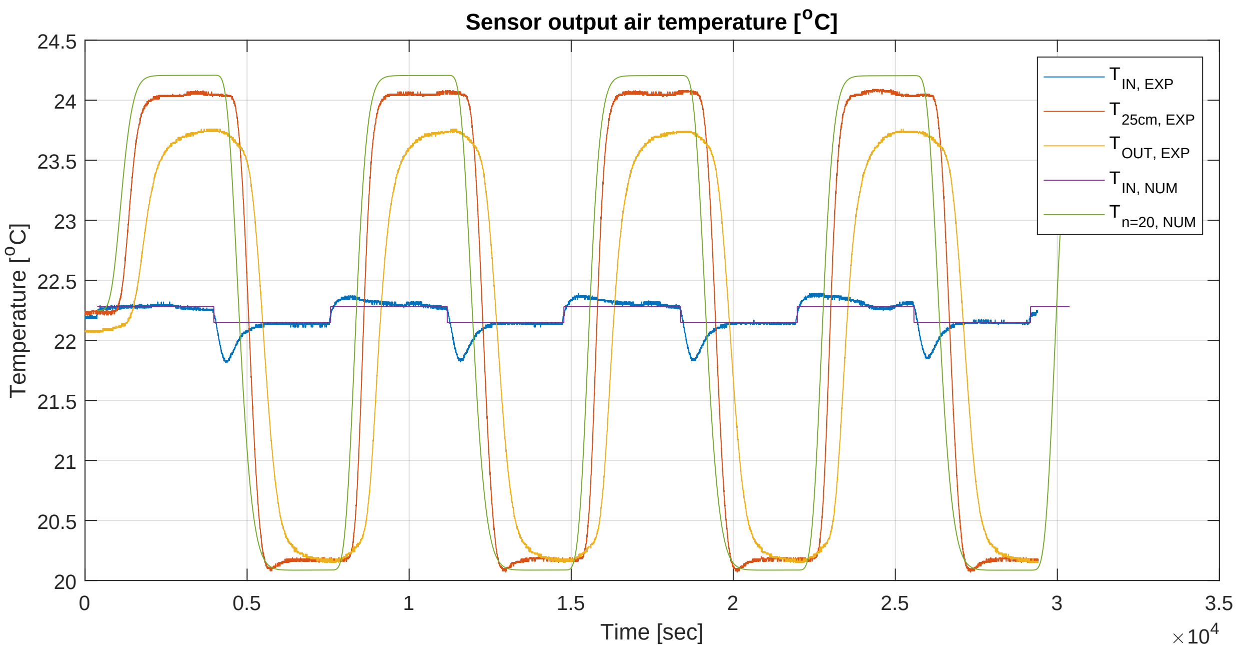


Figure 3.12: Comparison of experimental and numerical results for inlet and outlet air temperature.

Run 5

The experimental results for Run 5 are compared to the numerical results, at corresponding location. Location 13 of $50cm$ is evaluated at control volume $n = 5/20$.
Following input parameters are used in the model:

D	0.120 m
L	0.500 m
ϵ	0.36
Q	$1.667e-3\ m^3/s$
n	20
R_p	0.002 m
$T_{in,1}$	$21.80\ ^oC$
$T_{in,2}$	$21.80\ ^oC$
$m_{in,1}$	0.00940 kg/kg
$m_{in,2}$	0.00785 kg/kg
$T_{0,e}$	$21.80\ ^oC$
$m_{0,e}$	0.00785 kg/kg m

Table 3.5: PGC model input based on Run 5.

Used isotherm polynomial:

$$RH(w) = 1.667 - 33.65w + 265.6w^2 - 845w^3 + 969.9w^4 \tag{3.5}$$

Comparison of RH, X and T at 13 cm and control volume $n = 5\ of\ 20$:

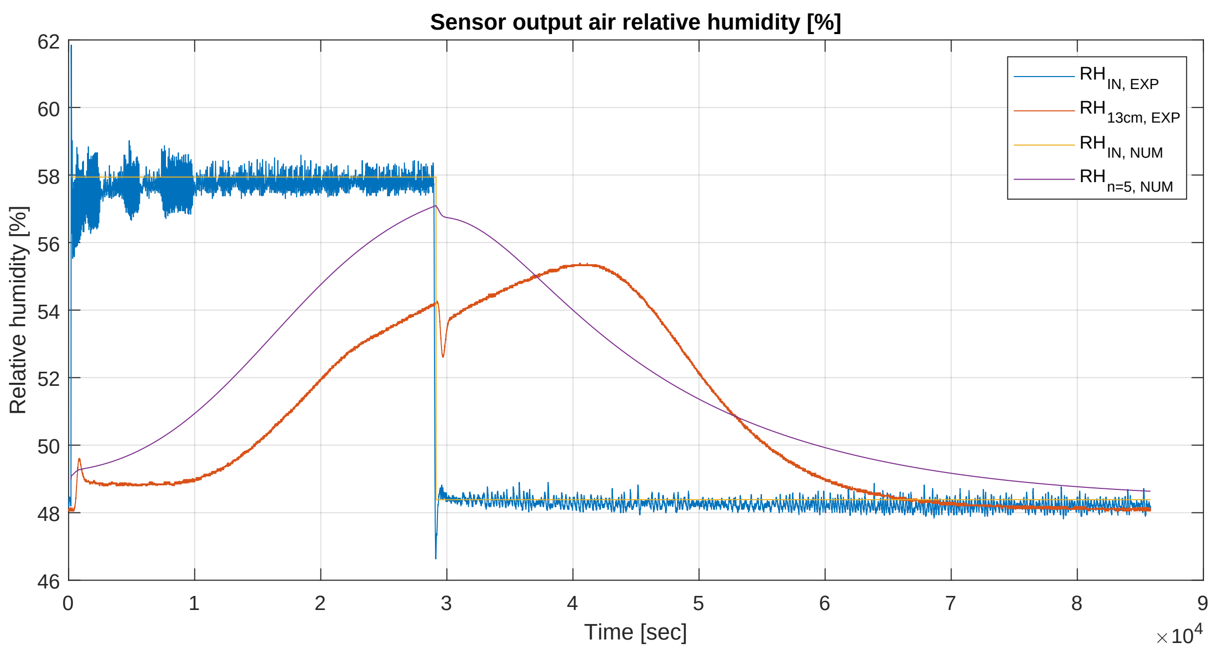


Figure 3.13: Comparison of experimental and numerical results for relative air humidity at $13\ cm$ and $n = 5$.

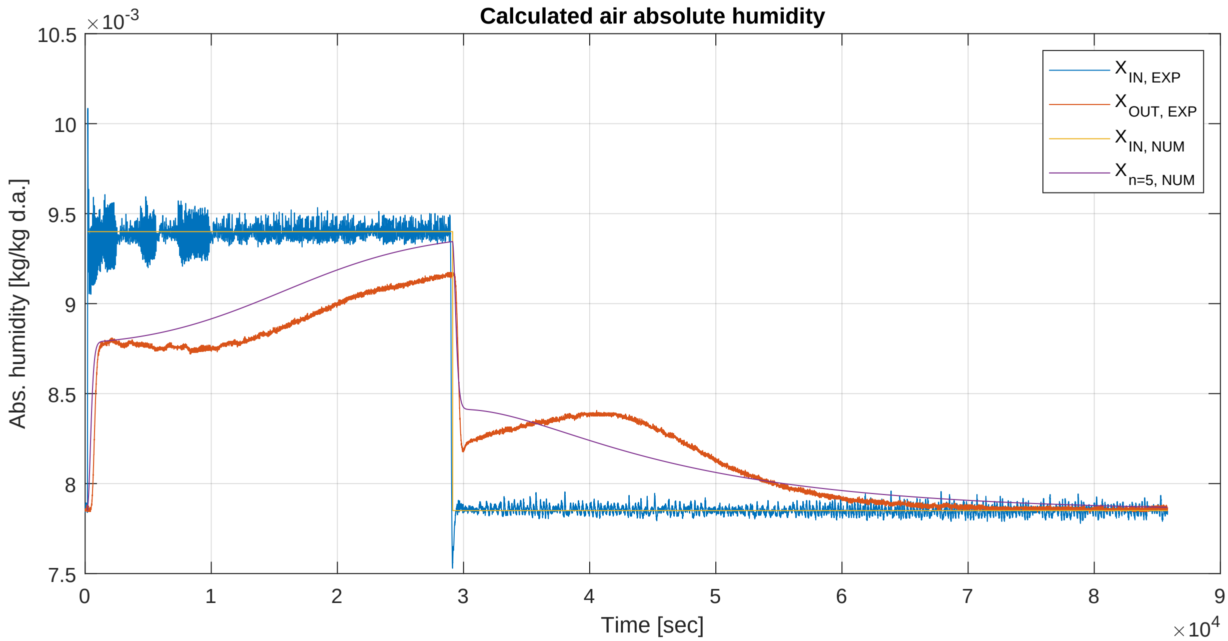


Figure 3.14: Comparison of experimental and numerical results for absolute air humidity at $13\ cm$ and $n = 5$.

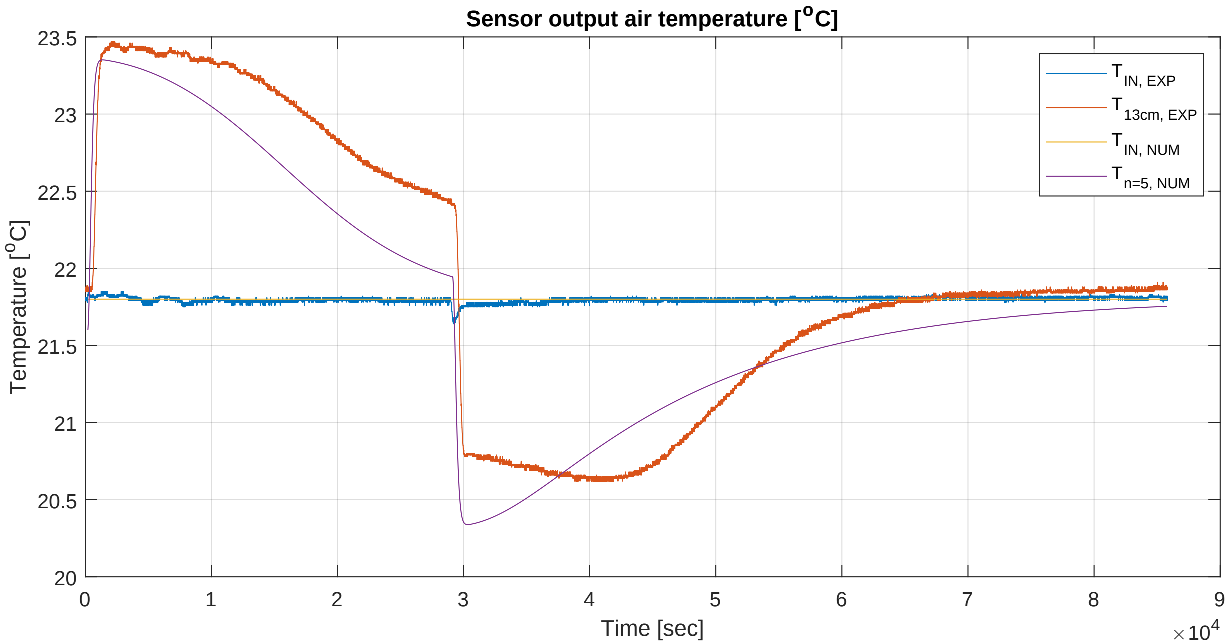


Figure 3.15: Comparison of experimental and numerical results for air temperature at 13 cm and $n = 5$.

The air conditions at outlet are compared for experimental and numerical results as well. Air leaving control volume $n = 20$ is evaluated as outlet air. In the experiment, temperature drops at the outlet. For this reason, experimental results at outlet as well as at $38\ cm$ are presented, for both temperature and relative humidity.

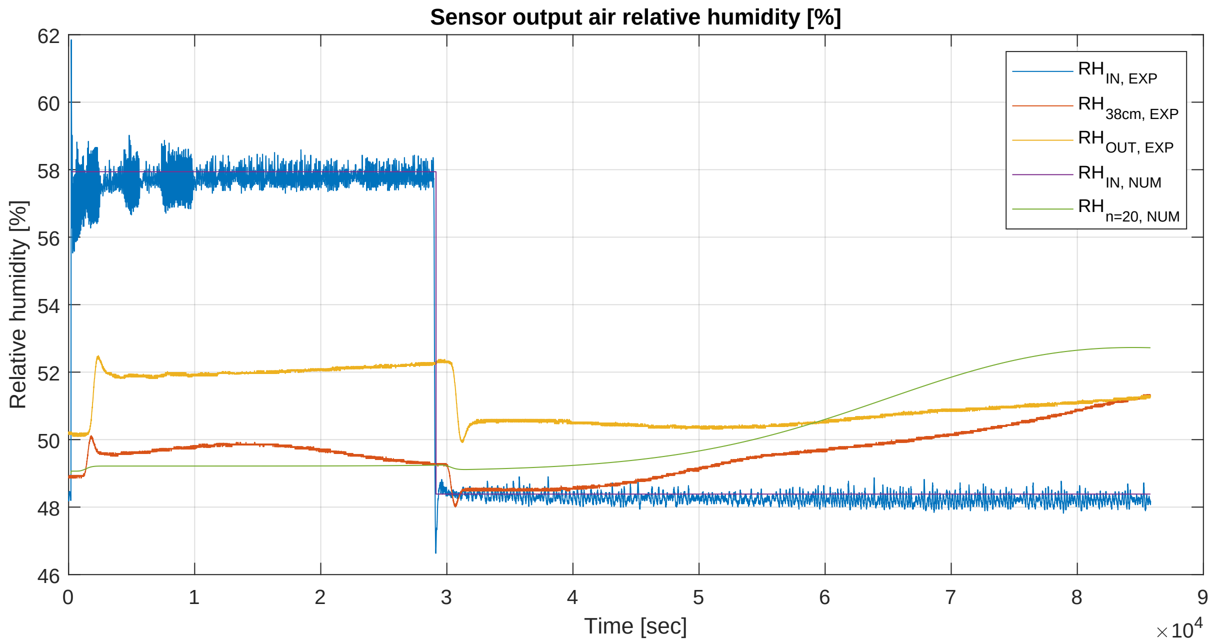


Figure 3.16: Comparison of experimental and numerical results for inlet and outlet relative air humidity.

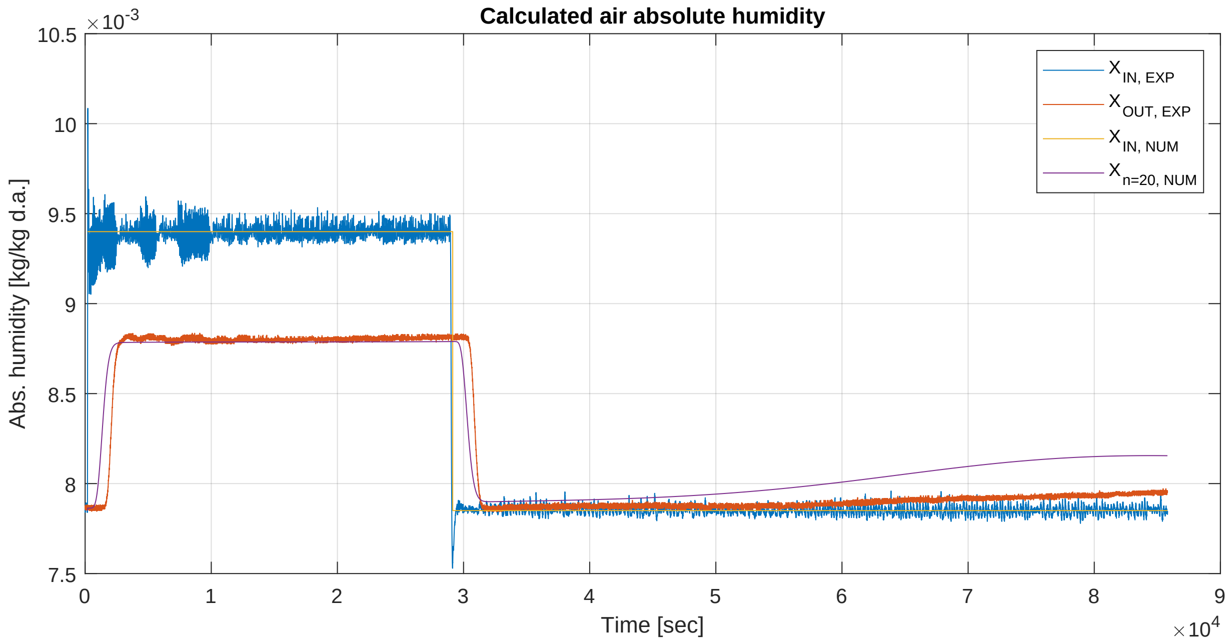


Figure 3.17: Comparison of experimental and numerical results for inlet and outlet absolute air humidity.

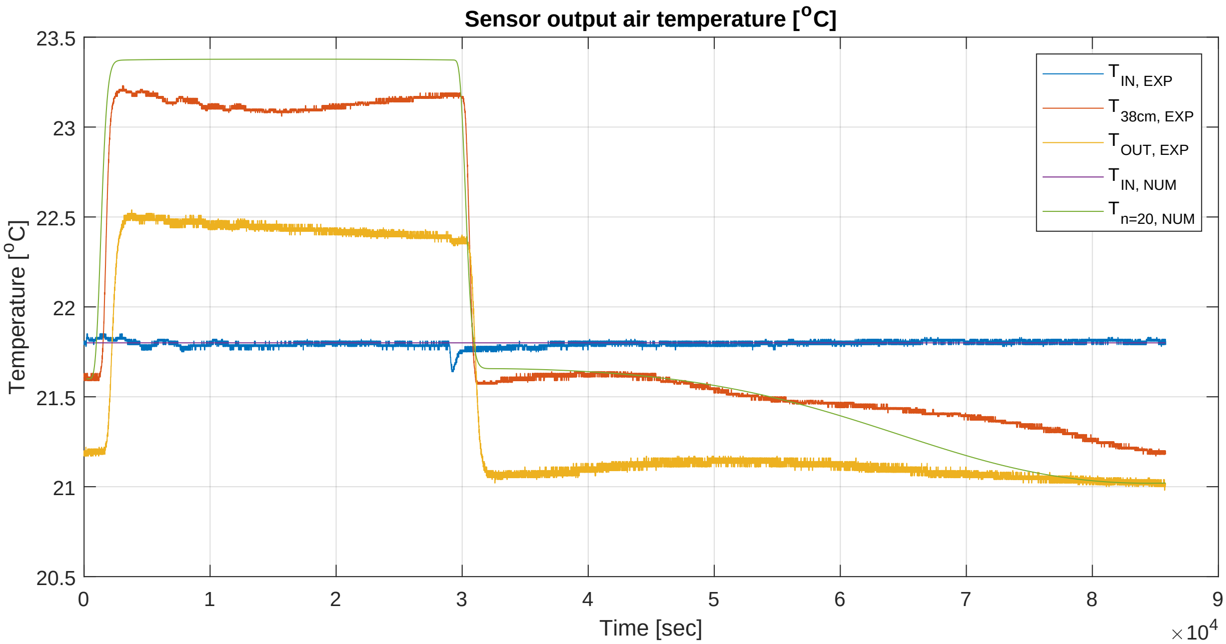


Figure 3.18: Comparison of experimental and numerical results for inlet and outlet air temperature.

Run 6

Following input parameters are used in the model:

D	0.120 m
L	0.310 m
ϵ	0.28
Q	$1.667e-3\ m^3/s$
n	20
R_p	0.001 m
$T_{in,1}$	$21.40\ ^oC$
$T_{in,2}$	$21.40\ ^oC$
$m_{in,1}$	0.00934 kg/kg
$m_{in,2}$	0.00785 kg/kg
$T_{0,e}$	$21.50\ ^oC$
$m_{0,e}$	0.00775 kg/kg m

Table 3.6: PGC model input based on Run 6.

Used isotherm polynomial:

$$RH(w) = 0.008263 + 4.145w - 9.279w^2 + 7.938w^3 \tag{3.6}$$

Comparison of RH, X and T at $13\ cm$ and control volume $n = 8\ of\ 20$:

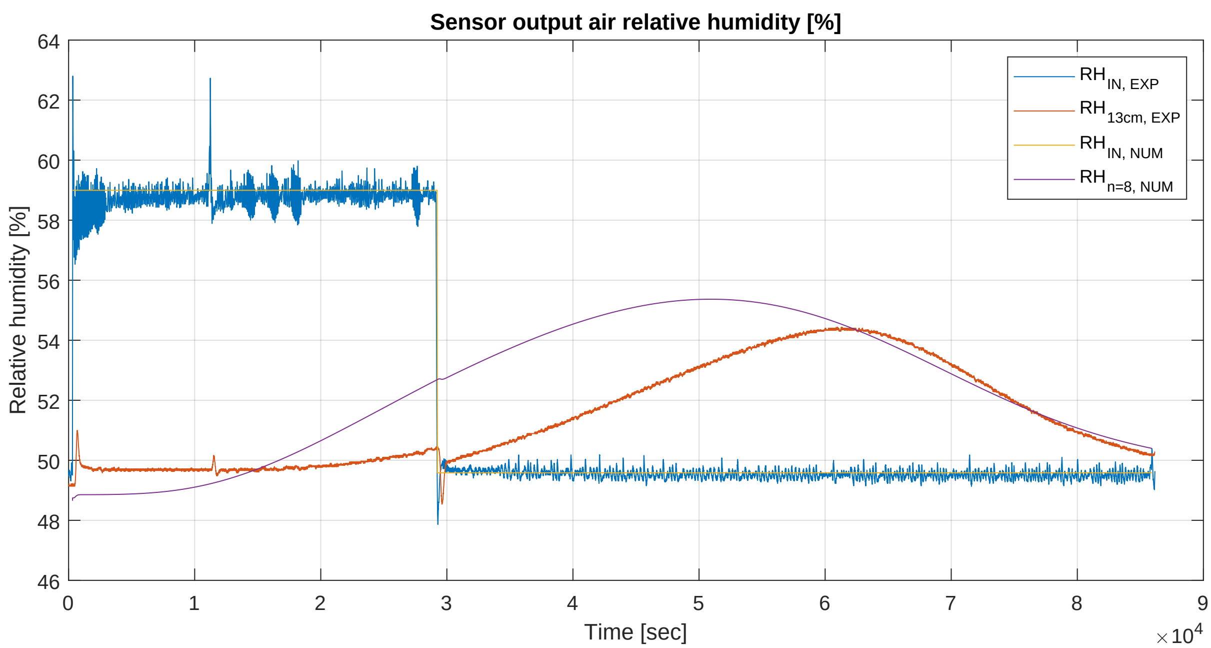


Figure 3.19: Comparison of experimental and numerical results for relative air humidity at $13\ cm$ and $n = 8$.

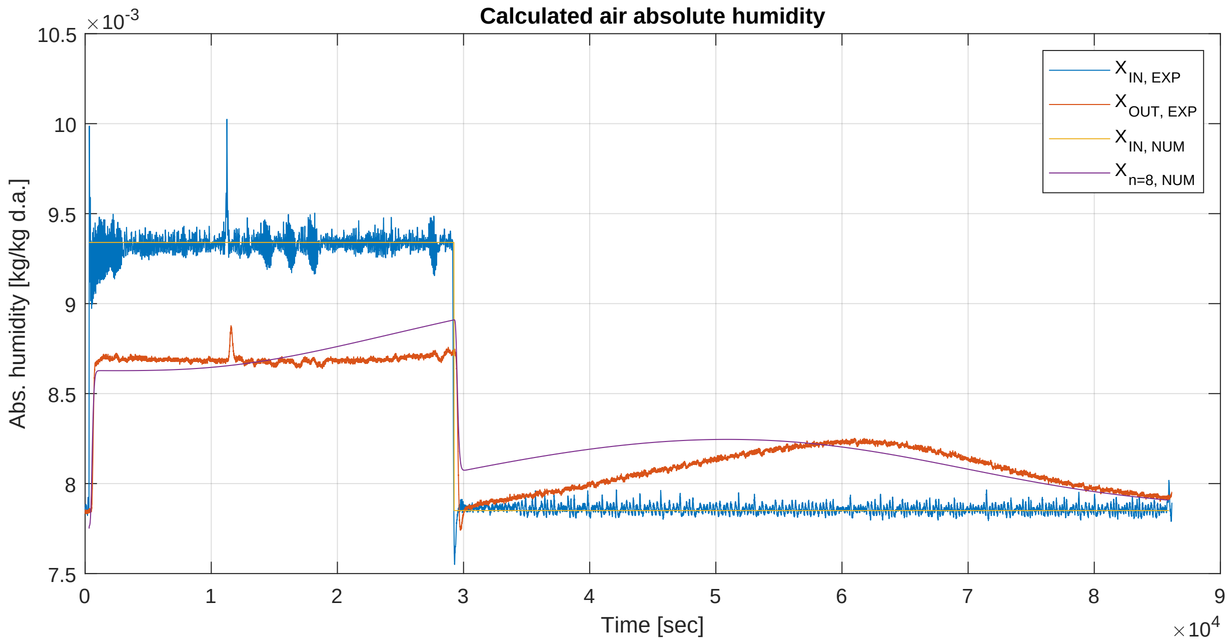


Figure 3.20: Comparison of experimental and numerical results for absolute air humidity at $13\ cm$ and $n = 8$.

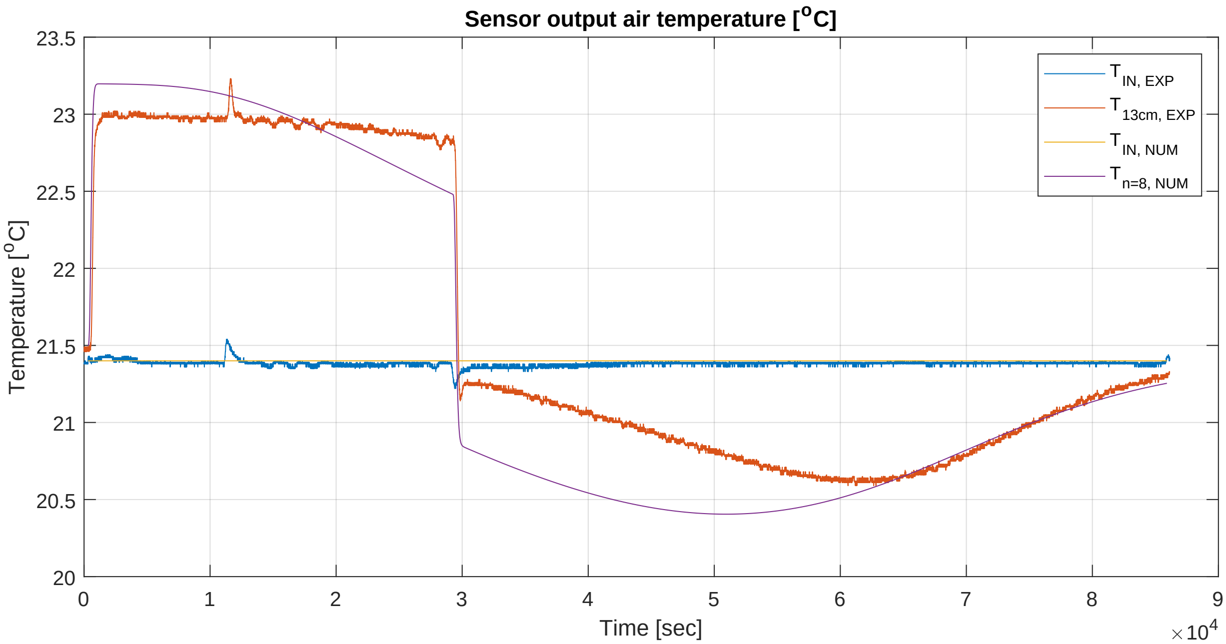


Figure 3.21: Comparison of experimental and numerical results for air temperature at 13 cm and $n = 8$.

The following figures present the experimental and numerical results of outlet air. Relative humidity and temperature are presented for $25\ cm$ as well as outlet.

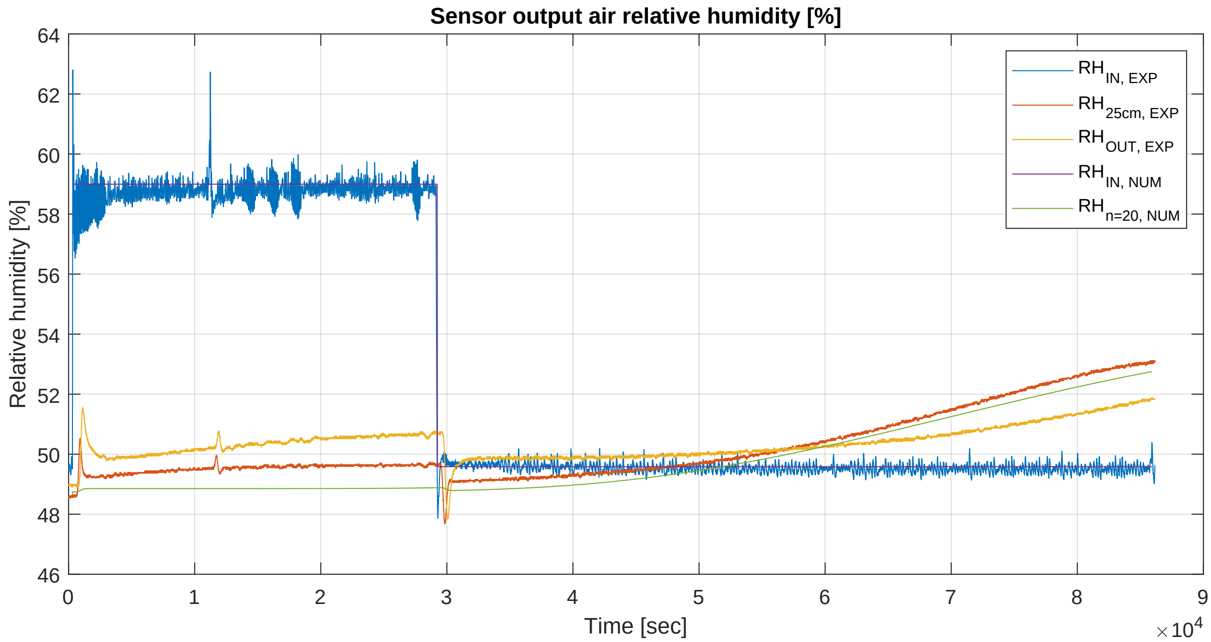


Figure 3.22: Comparison of experimental and numerical results for inlet and outlet relative air humidity.

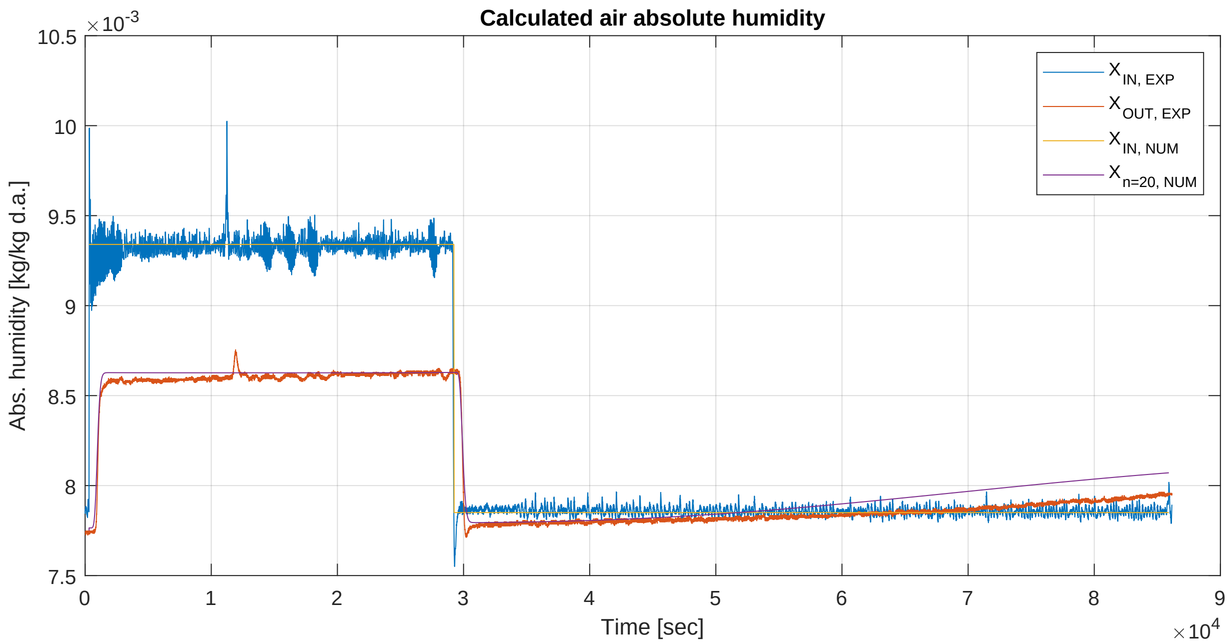


Figure 3.23: Comparison of experimental and numerical results for inlet and outlet absolute air humidity.

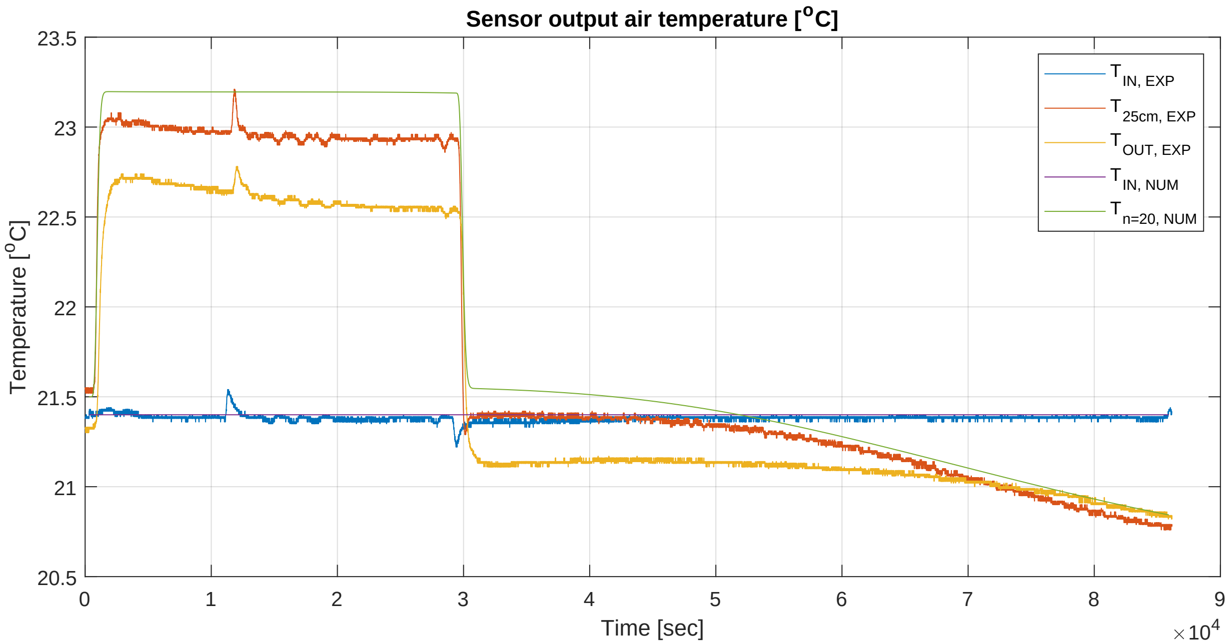


Figure 3.24: Comparison of experimental and numerical results for inlet and outlet air temperature.

Run 7

Following input parameters are used in the model:

D	0.120 m
L	0.260 m
ϵ	0.36
Q	$1.667e-3\ m^3/s$
n	20
R_p	0.002 m
$T_{in,1}$	$20.60\ ^oC$
$T_{in,2}$	$20.60\ ^oC$
$m_{in,1}$	0.00920 kg/kg
$m_{in,2}$	0.00770 kg/kg
$T_{0,e}$	$20.60\ ^oC$
$m_{0,e}$	0.00770 kg/kg m

Table 3.7: PGC model input based on Run 7.

Used isotherm polynomial:

$$RH(w) = 0.782 - 16.74w + 157.4w^2 - 556.8w^3 + 700.1w^4 \tag{3.7}$$

Comparison of RH, X and T at $13\ cm$ and control volume $n = 10\ of\ 20$:

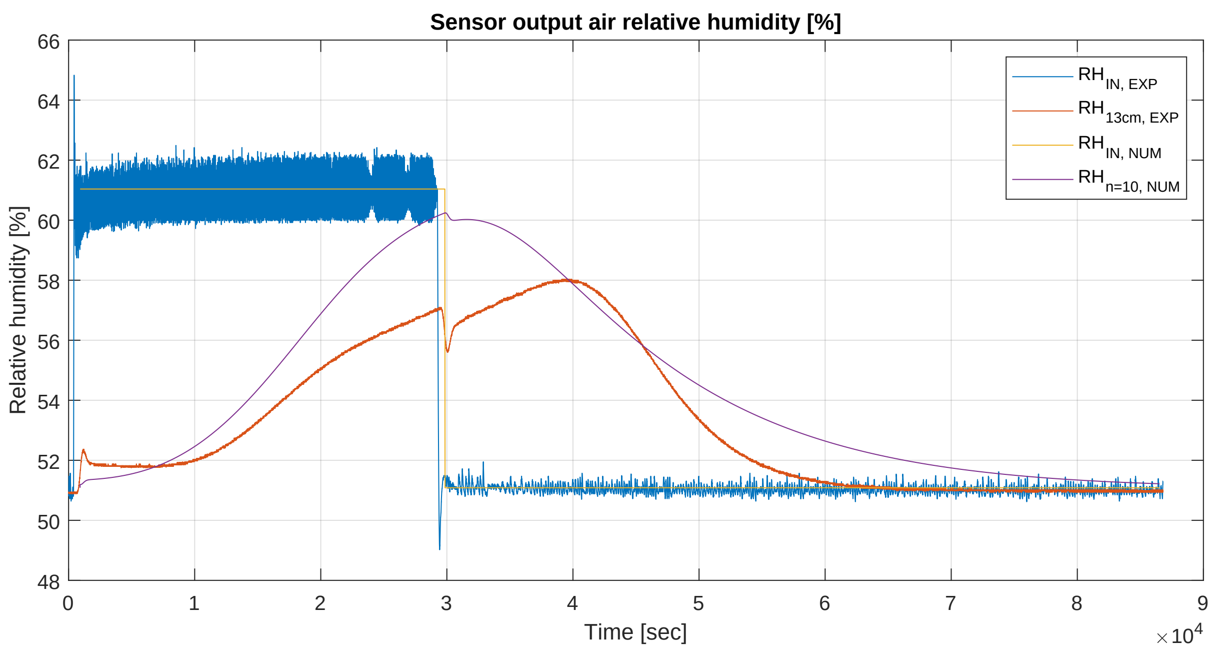


Figure 3.25: Comparison of experimental and numerical results for relative air humidity at $13\ cm$ and $n = 10$.

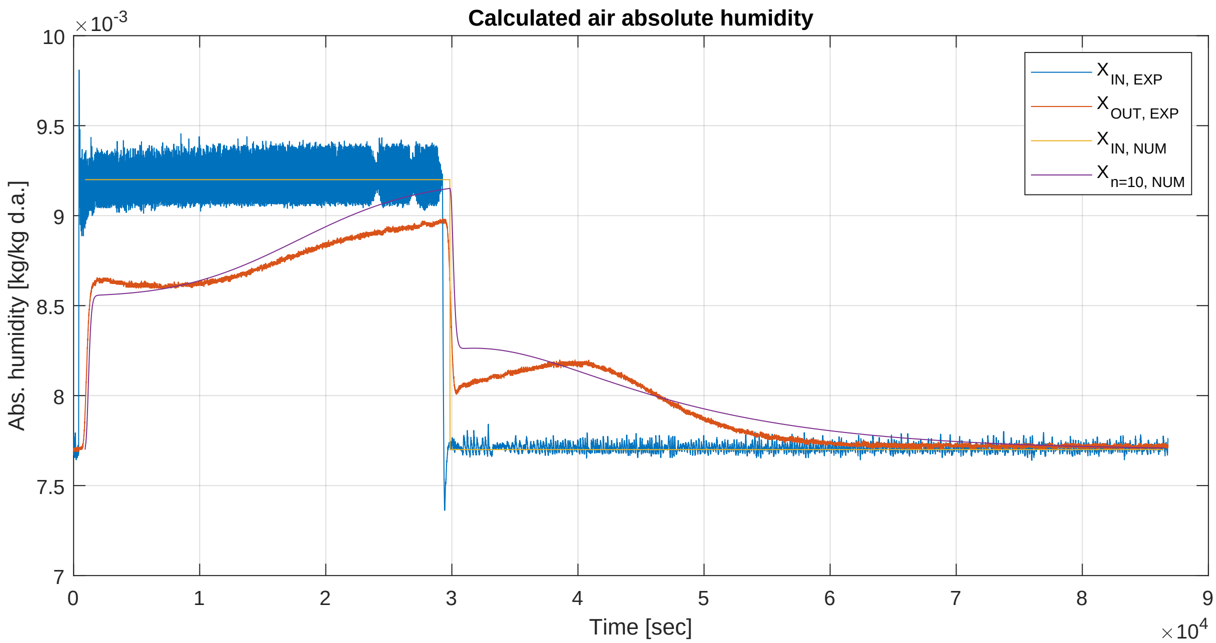


Figure 3.26: Comparison of experimental and numerical results for absolute air humidity at $13\ cm$ and $n = 10$.

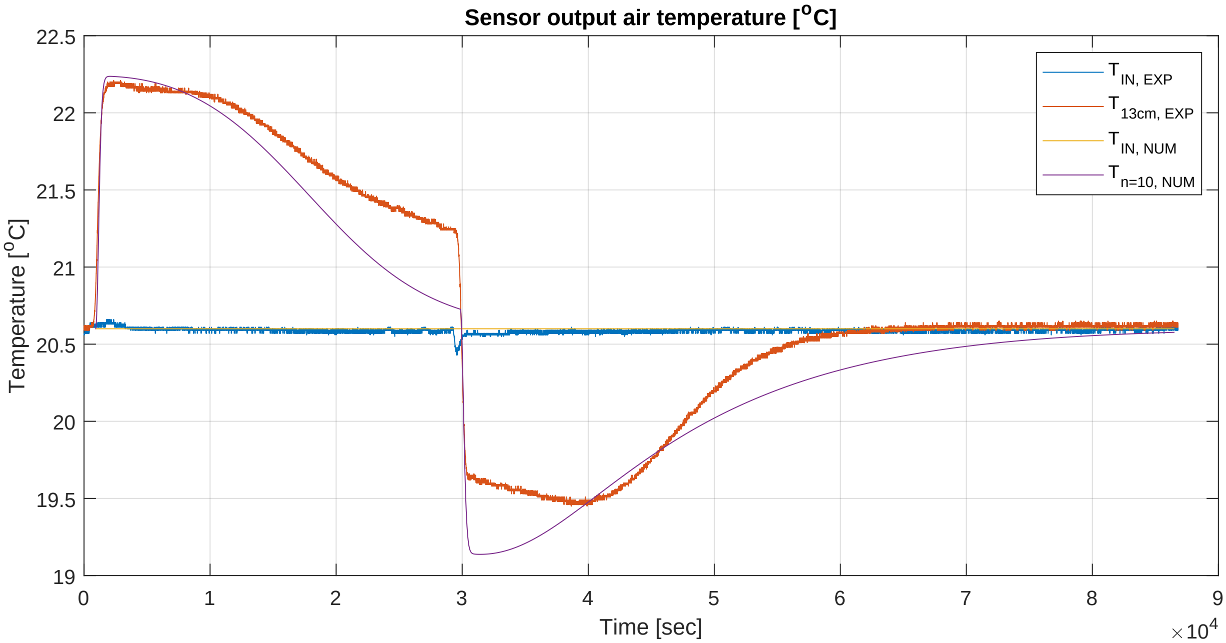


Figure 3.27: Comparison of experimental and numerical results for air temperature at 13 cm and $n = 10$.

The following figures present the experimental and numerical results of outlet air. Relative humidity and temperature are presented for $25\ cm$ as well as outlet.

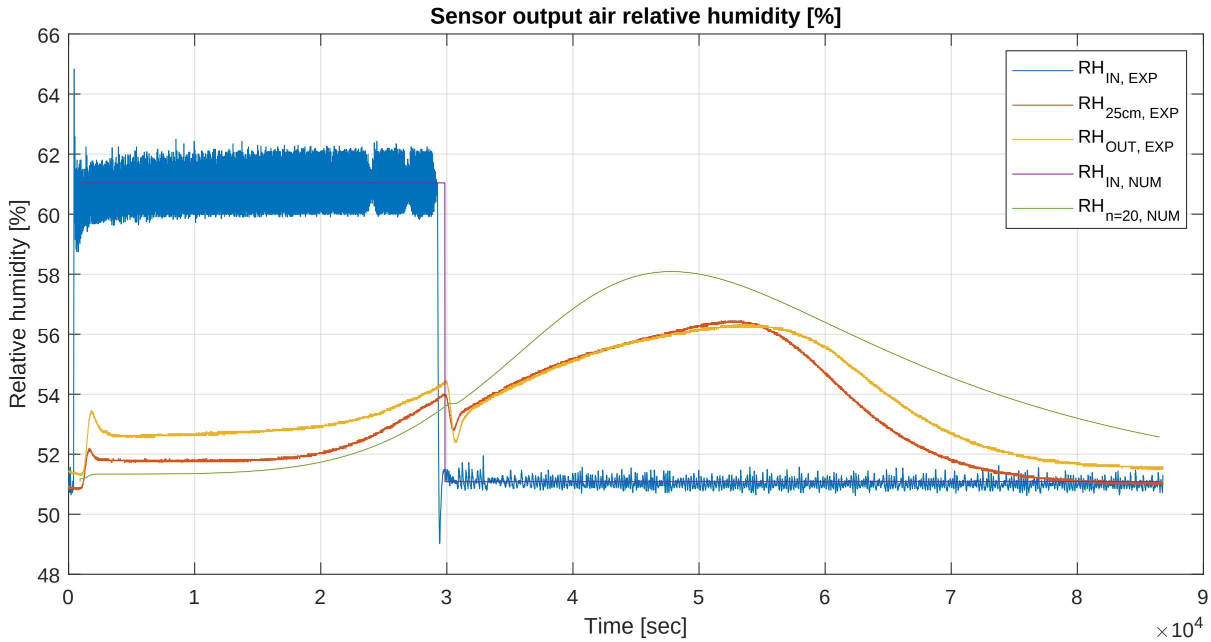


Figure 3.28: Comparison of experimental and numerical results for inlet and outlet relative air humidity.

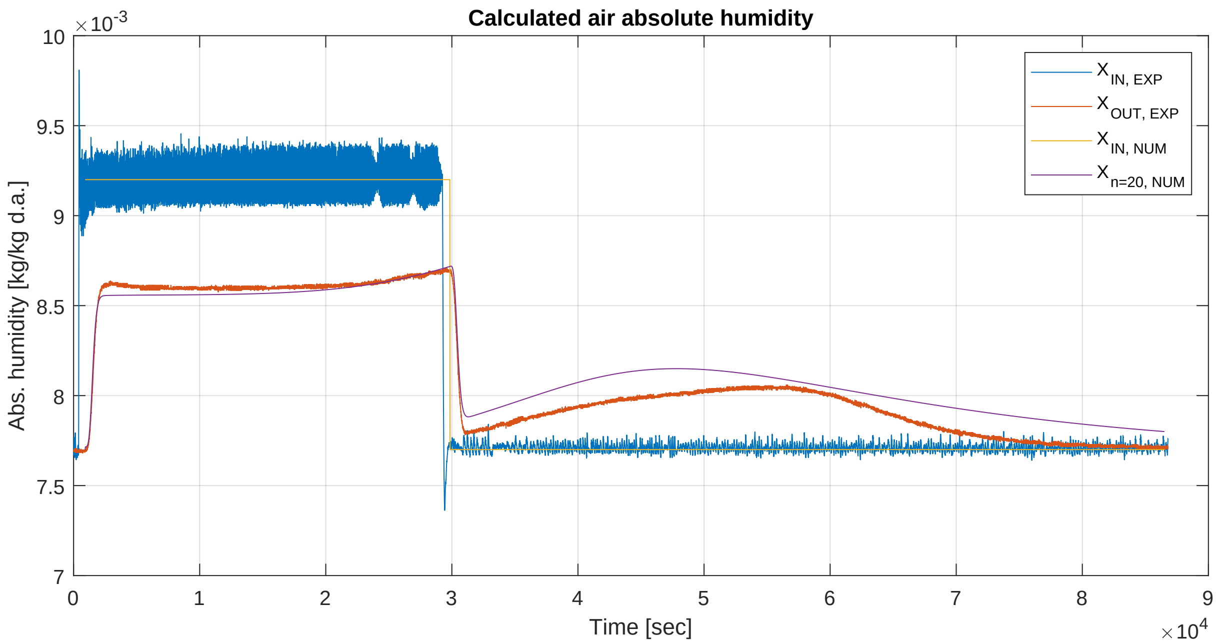


Figure 3.29: Comparison of experimental and numerical results for inlet and outlet absolute air humidity.

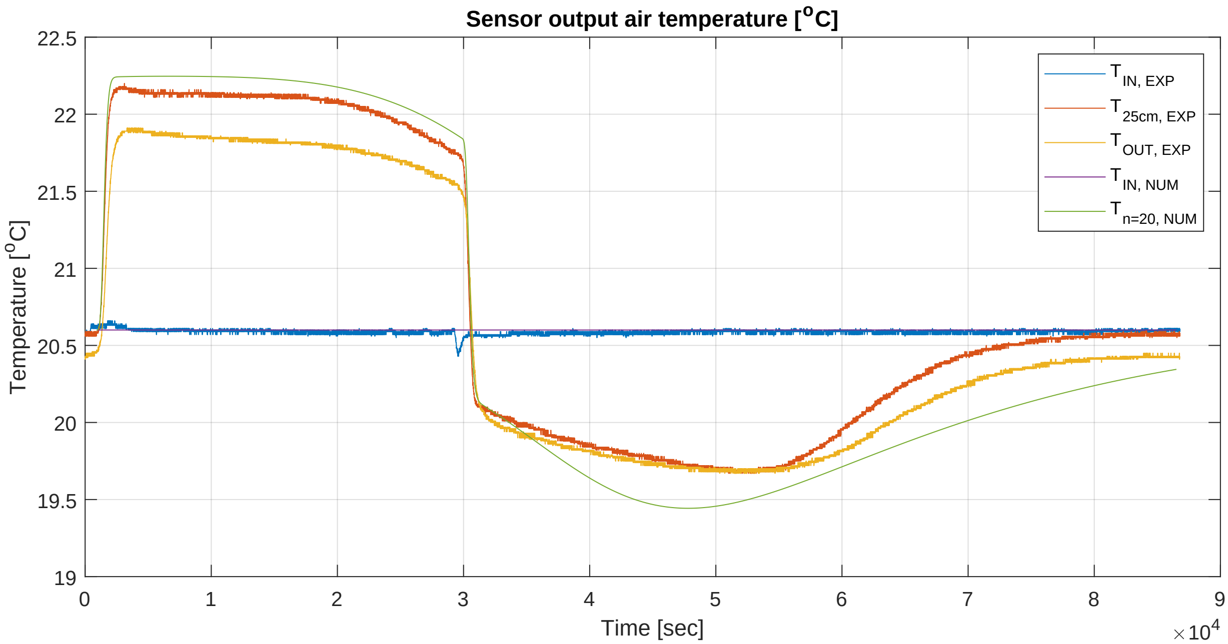


Figure 3.30: Comparison of experimental and numerical results for inlet and outlet air temperature.

Run 8

Following input parameters are used in the model:

D	0.120 m
L	0.285 m
ϵ	0.36
Q	$1.667e-3\ m^3/s$
n	20
R_p	0.002 m
$T_{in,1}$	$20.60\ ^oC$
$T_{in,2}$	$20.60\ ^oC$
$m_{in,1}$	0.00923 kg/kg
$m_{in,2}$	0.00768 kg/kg
$T_{0,e}$	$20.60\ ^oC$
$m_{0,e}$	0.00770 kg/kg m

Table 3.8: PGC model input based on Run 8.

Used isotherm polynomial:

$$RH(w) = 0.005046 + 0.5135w + 19.01w^2 - 80.69w^3 + 97.96w^4 \tag{3.8}$$

Comparison of X, RH and T at $13\ cm$ and control volume $n = 9\ of\ 20$.

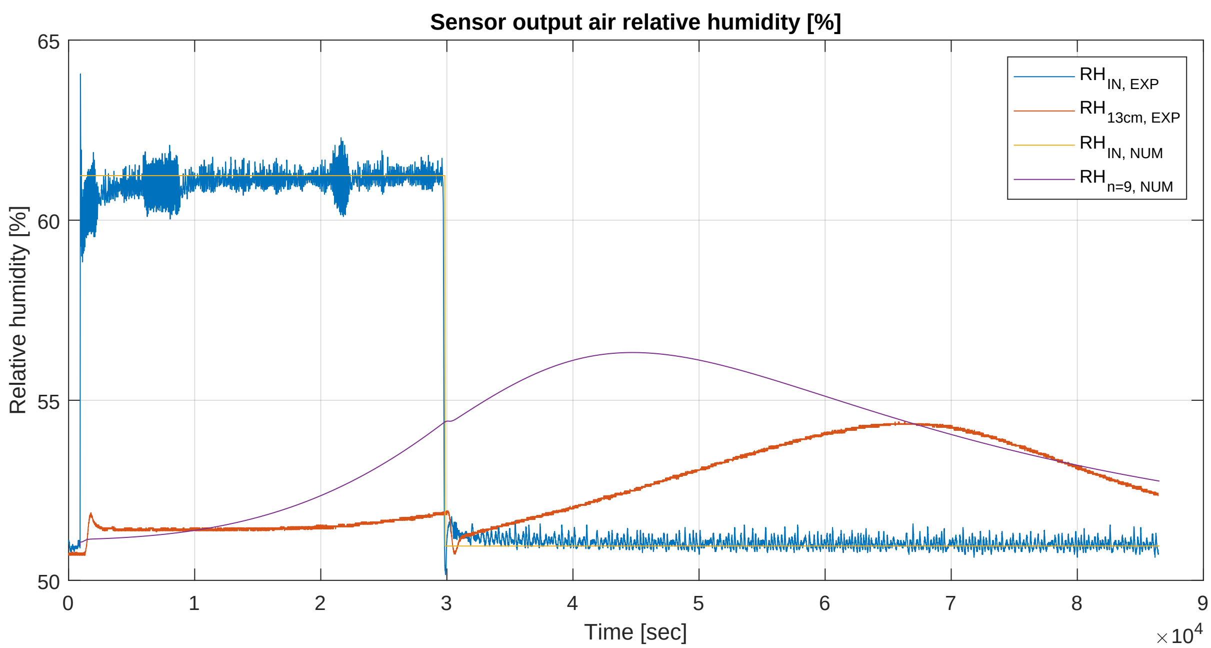


Figure 3.31: Comparison of experimental and numerical results for relative air humidity at $13\ cm$ and $n = 9$.

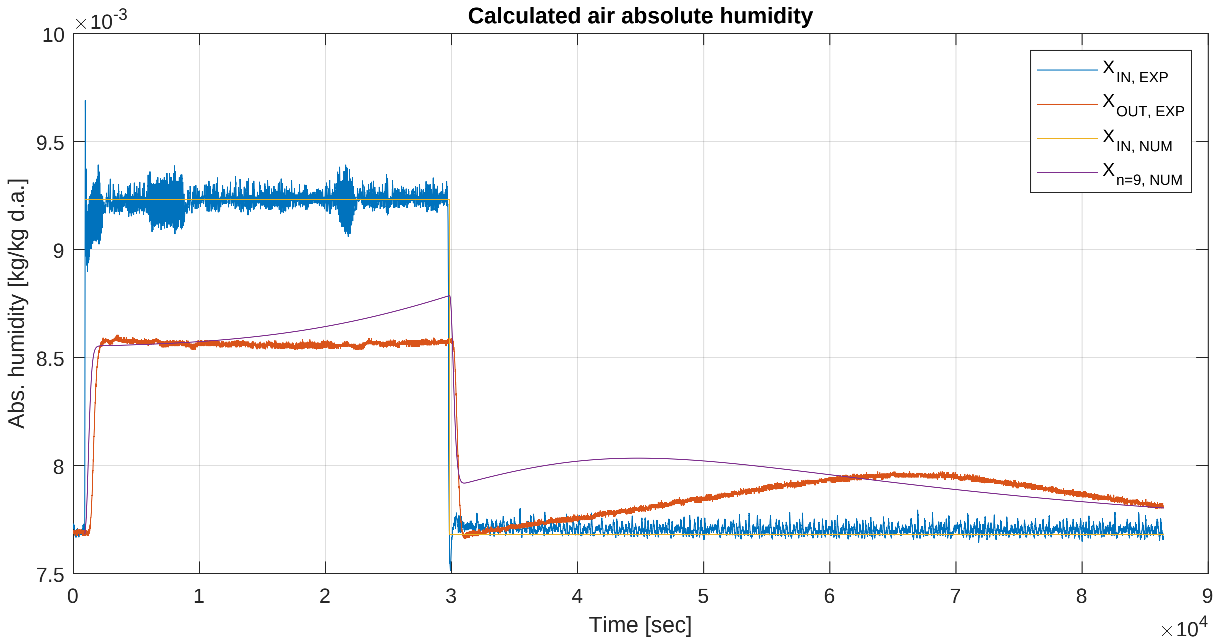


Figure 3.32: Comparison of experimental and numerical results for absolute air humidity at $13\ cm$ and $n = 9$.

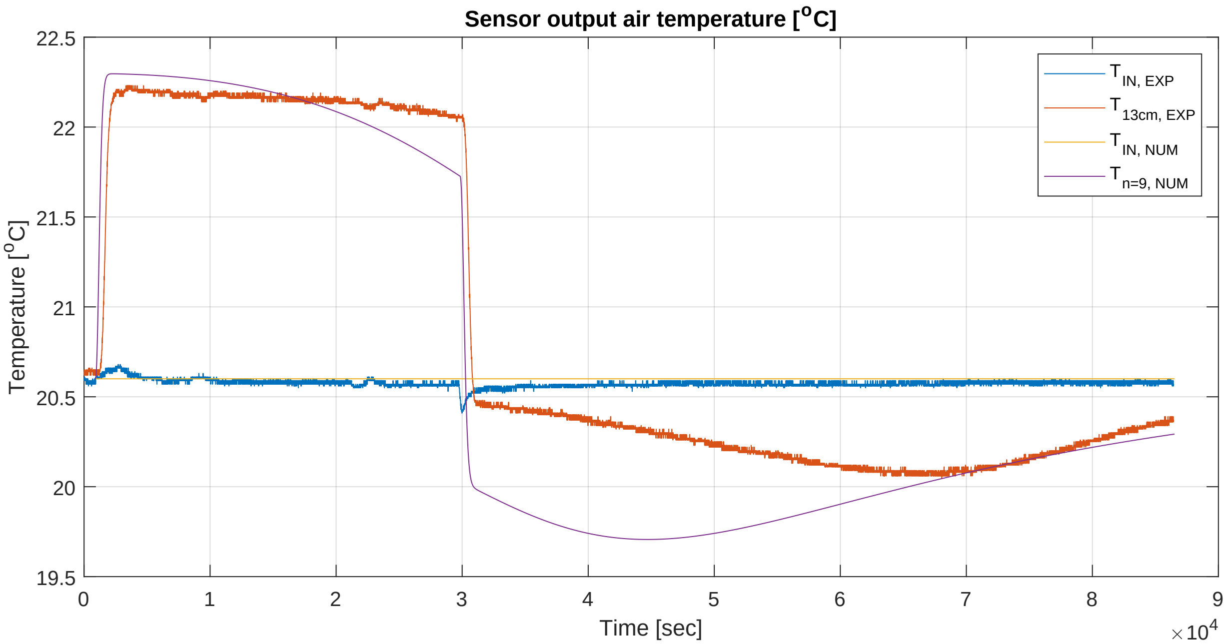


Figure 3.33: Comparison of experimental and numerical results for air temperature at $13\ cm$ and $n = 9$.

The following figures present the experimental and numerical results of outlet air. Relative humidity and temperature are presented for $25\ cm$ as well as outlet.

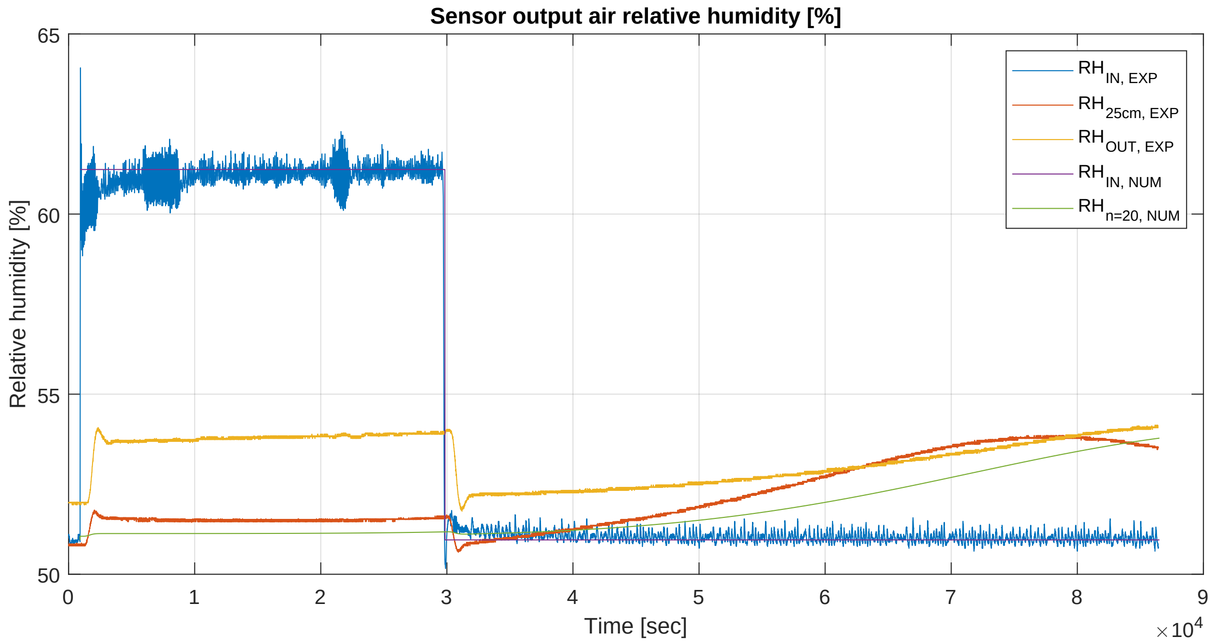


Figure 3.34: Comparison of experimental and numerical results for inlet and outlet relative air humidity.

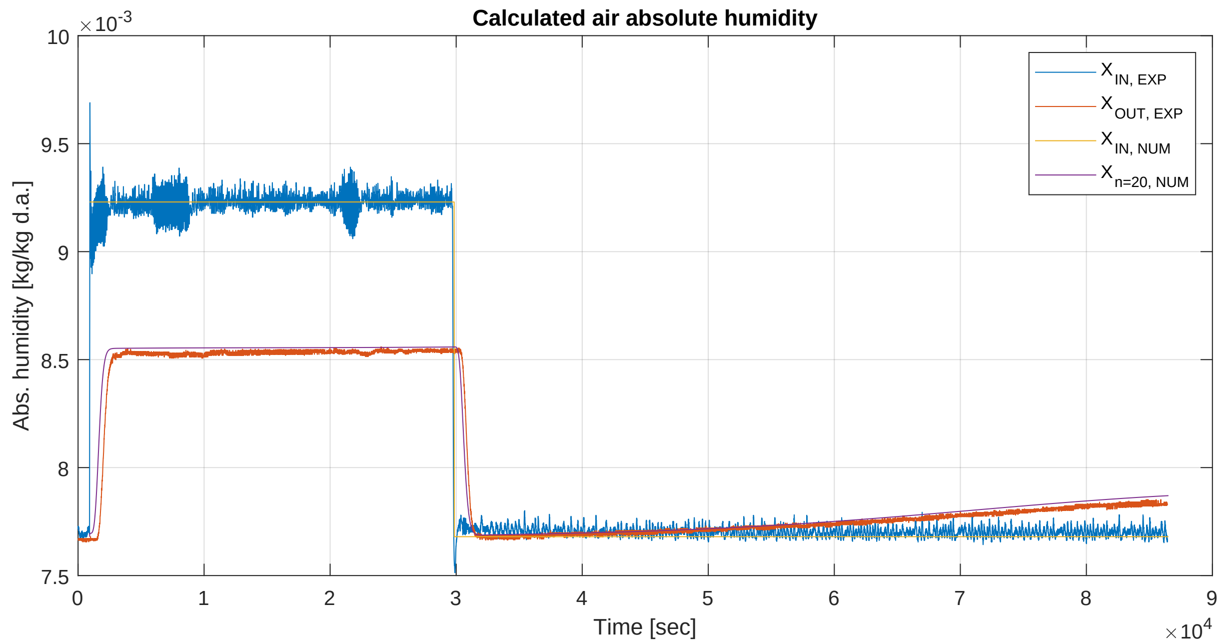


Figure 3.35: Comparison of experimental and numerical results for inlet and outlet absolute air humidity.

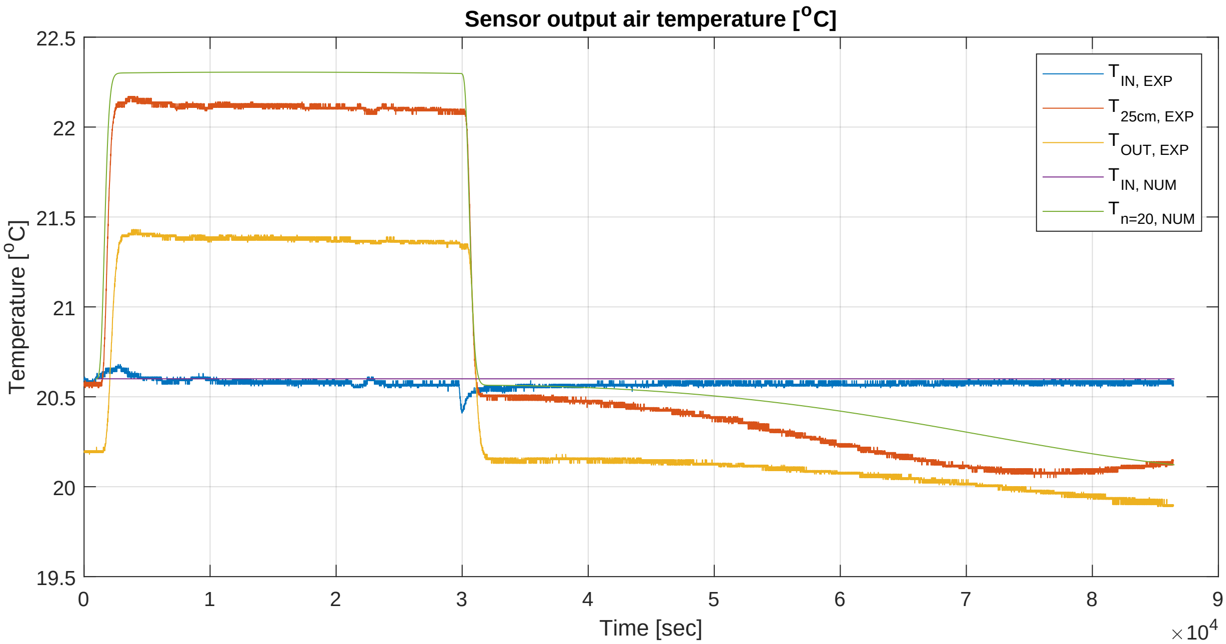


Figure 3.36: Comparison of experimental and numerical results for inlet and outlet air temperature.