An experimental investigation of the influence of the expansion of the moist air on its relative humidity

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Abstract

The aim of this paper is an experimental investigation of the influence of the expansion of moist air on its relative humidity. Two capacitive sensors (Honeywell HIH-4000-100 and Humistar HTP-1) were used for the experiments. At first calibration of the Honeywell sensor was performed using Humistar sensor as a reference standard. Than air was saturated at five different levels of the relative humidity (29, 43, 54, 66 and 90%, respectively) in a small pressure vessel. An expansion was performed after each saturation and dependency of relative humidity on pressure was observed. Experimental results were compared to theoretical data obtained from ideal gas model.

Key-words: Relative humidity, moist air, expansion of the moist air

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1. Introduction

Moist air is mixture of dry air, which is composed from many gaseous components, and water vapor. Water can be present in form of the water vapor, in the liquid or solid state. Other particles such as dust can be present in the air, but these substances will not be considered in this paper.

Mixture of the dry air and water vapor is called moist air. If the water is present in the air only in gaseous state, it is a homogenous mixture. When the moist air contains water in liquid (water drops) or solid (snow, crystal of the ice) state, it is a heterogeneous mixture.

Some problems can be caused by the water contained in the air during the experiments in a high speed wind tunnel. Water can condensate and can even freeze. Measured data can be influenced by this phenomena. Holes of the pressure probe can be sealed by the ice. Measurement technique can be even damaged or destroyed by the crystals of ice.

Thermodynamics of the moist air is studied in the literature [**2-8**].

Main purpose of this work is to investigate of the behavior of the humidity sensor in the expansion of the moist air and to decide whether this approach can be used for the future sensor calibration.

2. Moist air

If the pressure of the air is equal or less than barometric pressure then ideal gas model can be used for the description of the moist air with high accuracy. Model of the ideal gas is described by the state equation in form:

$$\frac{p}{\rho} = rT, \tag{1}$$

where p is the air pressure, ρ is the air density, r is the specific gas constant and T is the thermodynamic temperature. For the ideal gas model, constant values of the isochoric and isobaric specific heat capacities are assumed.

The specific gas constant is defined as:

$$r_i = \frac{R}{M_i}, \tag{2}$$

where $R = 8314.41 J/(kmol \cdot K)$ is the universal gas constant and M_i are the molecular weights of the components of the air.

Based on the kinetic theory of gases Poisson constant can be calculated as:

$$\kappa = \frac{n+2}{n}, \tag{3}$$

where n is the number of the degree of freedom.

Isochoric and isobaric specific heat capacities can be calculated from Mayer equation (4) and from equation for Poisson constant (5):

$$r = c_p - c_v. \tag{4}$$

$$\kappa = \frac{c_p}{c_v}. \tag{5}$$

2.1. Dry air

Dry air contains of many gaseous components. Composition of the dry air is shown in Table 1.

Table 1. *Composition of the dry air, values are taken from [**7**]*

Gas	*Symbol*	*Volume fraction* (%)
Nitrogen	N_2	78.09000
Oxygen	O_2	20.95000
Argon	Ar	0.930000
Carbon dioxide	CO_2	0.030000
Neon	Ne	0.001800
Helium	He	0.000524
Krypton	Kr	0.000100
Xenon	Xe	0.000008
Hydrogen	H_2	0.000005
Ozone	O_3	0.000001

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Considering that more than 99% of the dry air is composed of two atomic gases, nitrogen and oxygen, the number of the degree of freedom is $n = 5$ and $\kappa = 1.4$.

2.2. Water vapor

Molecule of the water vapor is composed of two atoms of hydrogen and one atom of oxygen. Molecular weight of the water is $M = 18.012 kg/kmol$. Molecule of the water is nonlinear, therefore number of the degree of freedom is $n = 6$ and $\kappa = 1.33$.

2.3. Moist air

Moist air can be considered as ideal gas if the dry air and the water vapor are considered ideal as well. Equality of temperatures and volumes of the dry air and water vapor is assumed. The isochoric and isobaric specific heat capacities and specific gas constants of the dry air and the water vapor are listed in Table 2:

Table 2. *Parametres of the dry air and the water vapor, values are taken from [**7**]*

	c_p $(J/(kgK))$	c_v $(J/(kgK))$	r_p $(J/(kgK))$
Dry air	1004,71	717,65	287,12
Water Vapor	1860,07	1395,05	461,52

Pressure of the moist air is defined according to Dalton law as:

$$p_{ma} = p_{da} + p_{wv}, \tag{6}$$

where p_{da} is the partial pressure of the dry air and p_{wv} is the partial pressure of the water vapor.

Weight of the moist air is given by:

$$m_{ma} = m_{da} + m_{wv}, \tag{7}$$

where m_{da} is the weight of the dry air and m_{wv} is the weight of the water vapor.

Based on equation (7) and ideal gas model, density of the moist air can be written as:

$$\rho_{ma}(p, T) = \rho_{da}(p, T) + \rho_{wv}(p, T), \tag{8}$$

where ρ_{da} is the density of the dry air and ρ_{wv} is the density of the water vapor.

2.3.1. Partial pressure of the water vapor

Pressure of the moist air is the sum of the partial pressures of the dry air and water vapor. Partial pressure of the water vapor can be divided into three regions:

- Partial pressure of the water vapor is less than pressure of the saturated vapor. Water vapor is in gaseous state and the mixture is homogenous.
- Partial pressure of the water vapor is equal to pressure of the saturated vapor. Limit of the saturation was reached in this case.
- Partial pressure of the water vapor is higher than pressure of the saturated vapor. Liquid water is condenses in this case.

2.3.2. Dew point

A dew point is an experimentally measurable quantity. Based on a measurement of the temperature of the dew point, humidity of the air can be determined. Temperature of the dew point is the temperature when the air is saturated by the water vapor at isobaric cooling. With further isobaric cooling water condenses.

2.3.3. Humidity of the air

Humidity of the air can be defined in many ways. Absolute humidity is defined as weight fraction of the water vapor contained in the unite quantities of the air.

Relative humidity is defined as:

$$\varphi = \frac{\rho_{wv}}{\rho''_{wv}} = \frac{\frac{p_{wv}}{rT}}{\frac{p''_{wv}}{rT}} = \frac{p_{wv}}{p''_{wv}}. \tag{9}$$

Relative humidity according equation (9) can reach values in the range $\langle 0 - 1 \rangle$. Dependencies of the partial pressures of the water vapor on the temperature is shown in Fig. 1 for different values of the relative humidity.

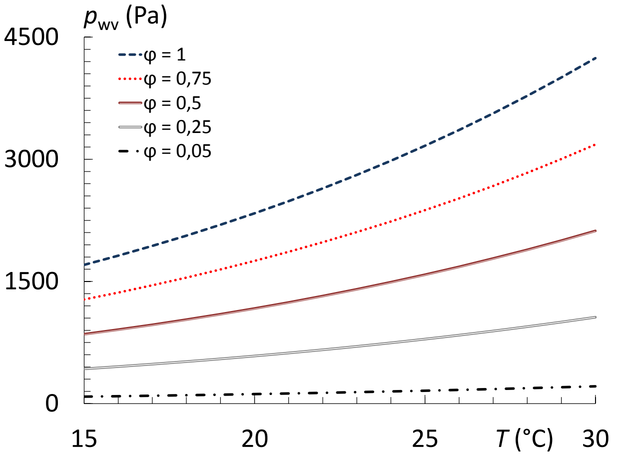

Fig. 1. *Dependencies of the partial pressure of the water vapor on the temperature for different values of the relative humidity, values are taken from [**2**].*

Specific humidity is defined as:

$$x = \frac{\rho_{wv}}{\rho_{da}}. \tag{10}$$

Based on equation above, equation (10) can be rewritten into:

$$x = 0.622 \frac{p''_{wv}}{p - p''_{wv}}. \tag{11}$$

3. Experimental setup and methods

Apparature for relative humidity measurement consists of a pressure vessel, a bottle of water, vacuum pump, tubes and sensors for the measurement.

3.1. Experimental aparature

Air was saturated in the bottle with water. Saturated air was blown from the bottle to the pressure vessel ($V = 0.0038\ m^3$) trough the gap in the bottom of the vessel using vacuum pump Busch Malburg SV 1003. Air was sucked from the vessel trough second gap in the vessel bottom to the vacuum pump and from the pump was blown back to the bottle with water. The sensors for humidity measurement, the thermocouple and the pressure transducer were placed in the lid of the pressure vessel.

After the air was saturated to the demanded level of the relative humidity, bottle with water was removed from the cycle, the gap in the vessel bottom was sealed and expansion was performed. Apparature for the measurement is shown in Fig. 2.

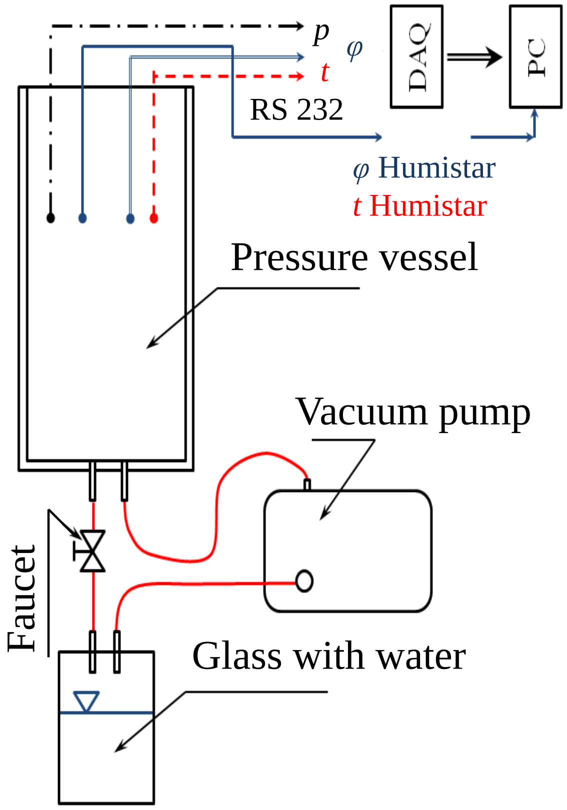

Fig. 2. *Measurement aparature.*

3.2. Devices and methods

3.2.1. Humidity and temperature measurement

For the relative humidity measurement, two sensors were used (Sensorica Humistar and Honeywell sensor, respectively). Parameters of the sensors are described below:

- Sensorica Humistar HTP-1 with range of measurement $0 - 100\%$ RH (Relative Humidity), with accuracy of $\pm 1\%$ rdg. at temperature 20^oC and in range $10 - 80\%$ RH.
- Honeywell HIH-4000-100 with range of measurement $0 - 100\%$ RH, with accuracy of 3.5% rdg. at temperature 25^oC.

Both sensors were capacitive, that means capacity of the sensors is dependent on the humidity [**9**]. Measured quantity is then voltage. Recommendation for the humidity measurement can be found in [**10**].

3.2.2. Pressure measurement

Barometric pressure was measured using pressure indicator Druck DPI 145 with accuracy of 0.013% FS.

Pressure in the vessel was measured using differential pressure transducer with range of $100 kPa$. Pressure difference between the pressure in the vessel and barometric pressure was measured. Accuracy of the transducer was 0.1% rdg. Prior to the experiment transducer was calibrated in the range of $0 - 100 kPa$ and calibration equation was set to $p = 20.10394E$, where E is the measured voltage.

3.3. Data processing

Experiment was performed with using LabView software. This program was developed for this experiment and is described in [**11**].

Measured data were processed in the MS Excel.

4. Results and discusion

4.1. Calibration of the Honeywell sensor

First of all calibration of the Honeywel sensor was performed. For calibration of the Honeywell sensor Humistar was set as a measurement standard due to its certified calibration. Air was saturated in the vessel as described above and dependency of the relative humidity at measured voltage was measured. The calibration curve for the Honeywell sensor was obtained. Curve is shown in Fig. 3.

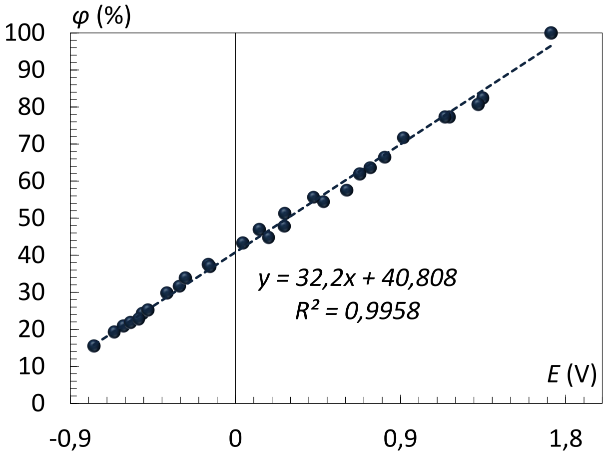

Fig. 3. *Calibration curve for the Honeywell sensor.*

From the calibration, equation for relative humidity was established as:

$$\varphi = 32.2E + 40.808. \tag{12}$$

4.2. Influence of air intake into the vessel

Due to the presence of two sensors for the relative humidity measurement, one termocouple and pressure transducer in the vessel lid and two gaps in the vessel bottom, vessel was not hermetically sealed. This fact was reflected in the air intake to the vessel during the expansion. For that reason test of air intake was performed. Air was sucked out from the vessel and than time of intake air into the vessel was measured. Result is shown in Fig. 4.

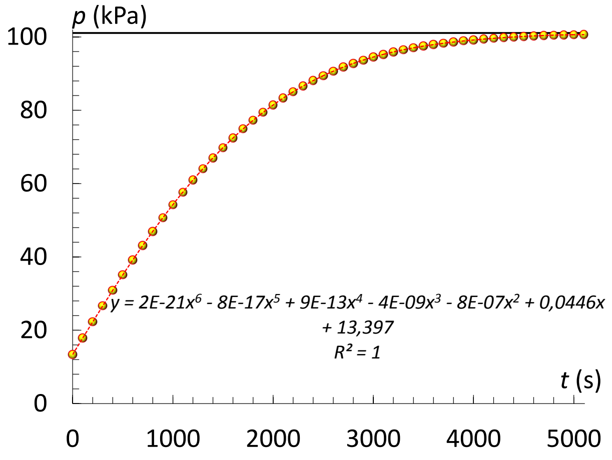

Fig. 4. *Intake of the air.*

4.3. Impact of the expansion of moist air at its relative humidity

Experiment was designed as expansion conducted isothermally and at constant value of specific humidity. Five expansions were performed from five different levels of saturation (29, 43, 54, 66 and 90 %, respectively). Some variations of the temperature during the measurement were observed and are shown in Fig. 5.

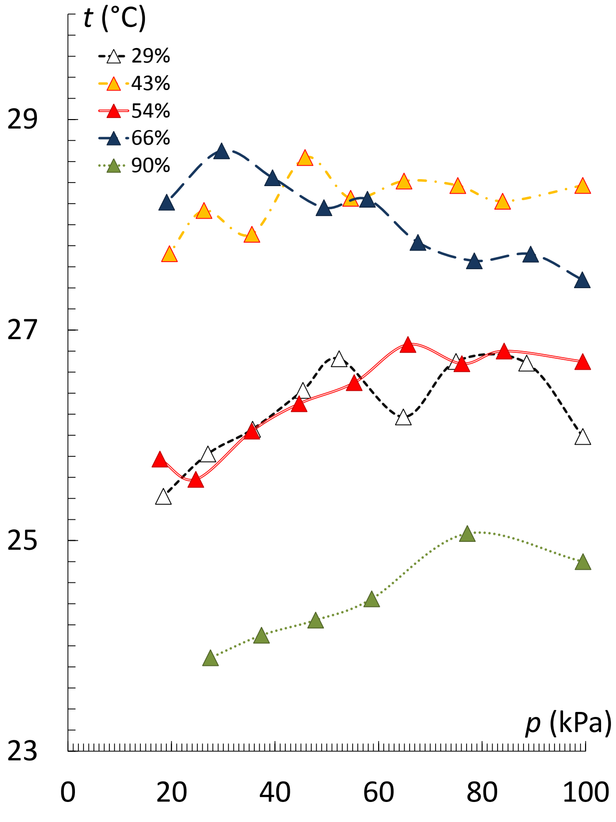

Fig. 5. *Temperature variation.*

The temperature variation during single measurement was not grater than 4^oC.

Measured dependencies of the relative humidity on the pressure is shown in Fig. 6. In the figure also theoretical dependencies are shown. Theoretical values were determined from equation for isotermal expansion:

$$\varphi_2 = \varphi_1 \frac{p''_{wv1}(t_1)}{p''_{wv2}(t_2)} \frac{p_{ma2}}{p_{ma1}} = \varphi_1 \frac{p_{ma2}}{p_{ma1}}, \tag{13}$$

where index 1 means initial condition and index 2 was final state.

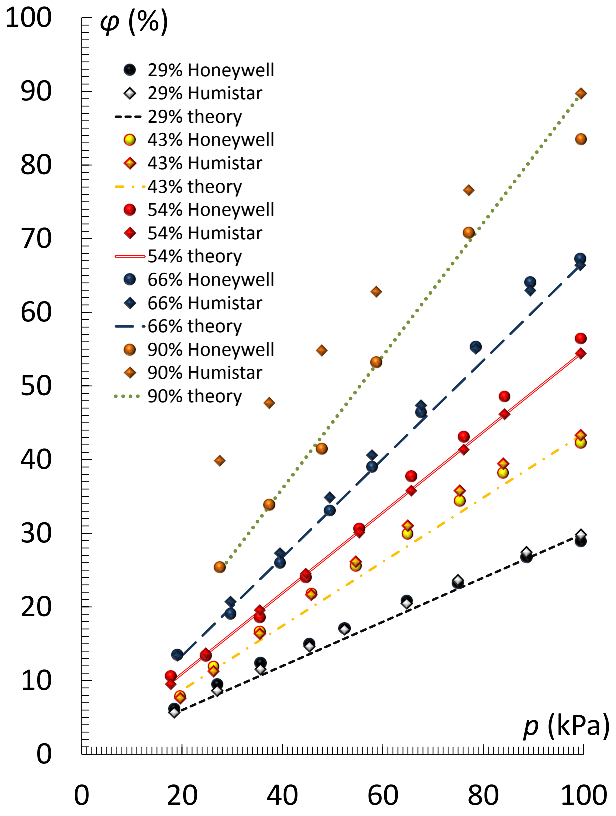

Fig. 6. *Dependencies of the relative humidity on the pressure compared to theory.*

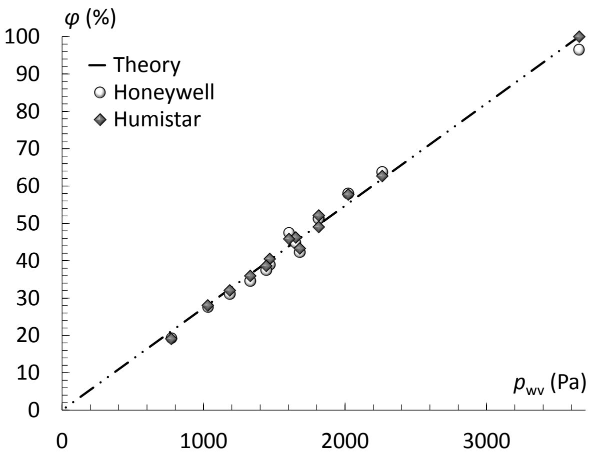

Fig. 7. *Measured data for temperature $T = 28^oC$ compared to theory.*

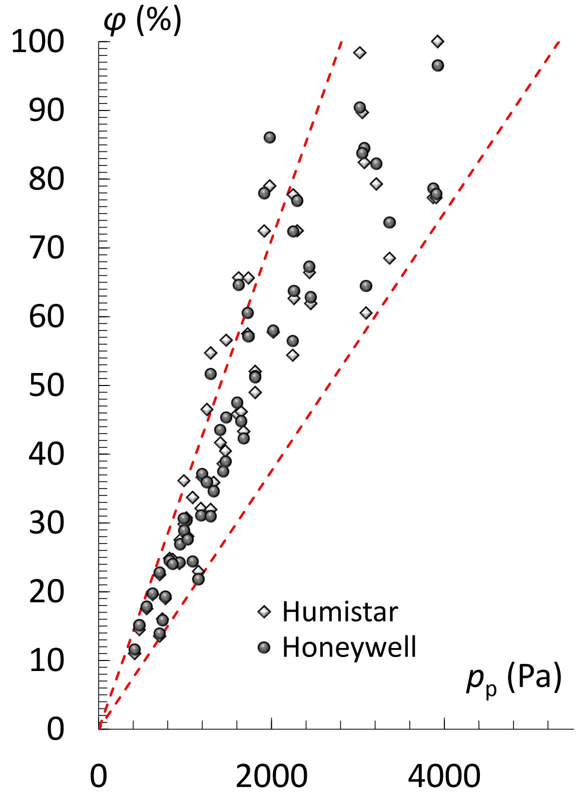

Fig. 8. *Dependency of the relative humidity on the partial pressure of the water vapor.*

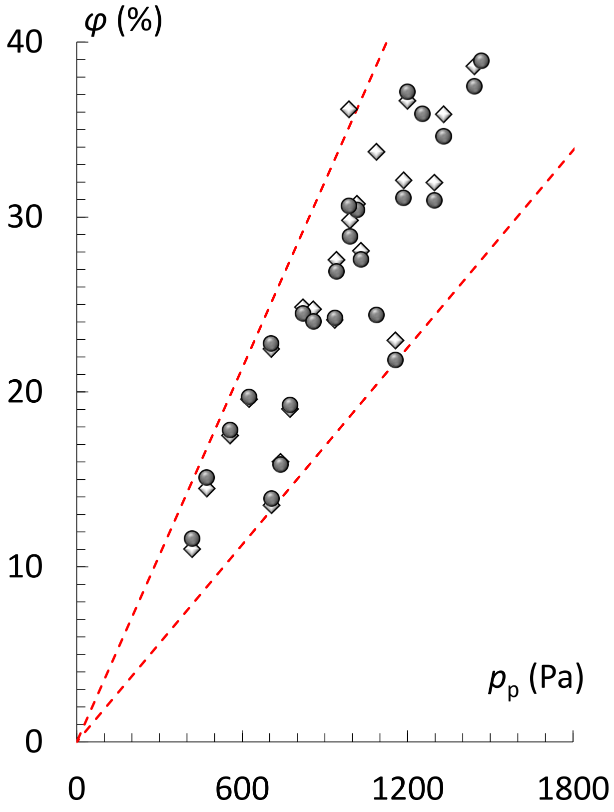

Fig. 9. *Dependency of the relative humidity on the partial pressure of the water vapor, detail for low values of the pressure.*

It is obvious, that theoretical values are in good agreement with measured data. Linear dependencies of the relative humidity on the pressures can be seen.

Only measured data from sensor Humistar for saturation at level 90% of the relative humidity is not in good agreement with theory. That was caused because of long response time of the sensor and a short time of the experiment.

For the temperature $T = 28^oC$ measured data was compared to theory according equation (13). This comparison is shown in Fig. 7.

Dependenciy of relative humidity on partial pressure of the water vapor was also evaluated. This evaluation is shown in Fig. 8. In Fig. 9 low values of the partial pressureis is shown a detail of the Fig. 8. Some variation in the temperature was observed during the experiment that means each expansion was performed at a different temperature. Range for the measured data is shown in the Fig. 8 and Fig.9 by red dashed line from that reason. As can be seen all the values are in good agreement with the theoretical boundaries.

The uncertainties for the temperature ($T = 28^oC$) were also established as shown in Fig. 10. It can be seen from the Fig. 10 almost all of the data coresponds with theoretical values.

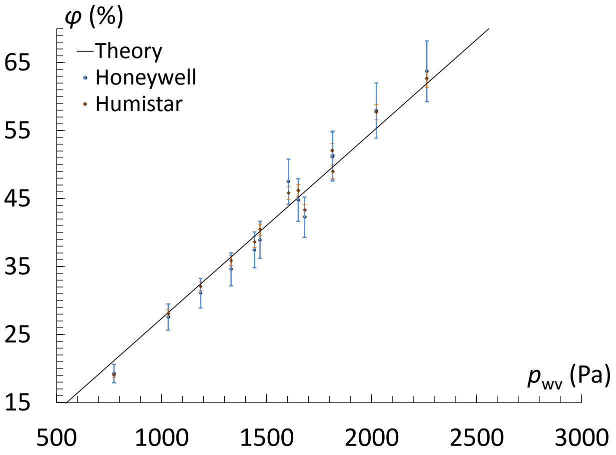

Fig. 10. *Uncertainties of the measurement for temperature $T = 28^oC$.*

5. Conclusion

An experimental investigation of the expansion of the moist air was performed. The aim of these experiments was to try out the equipment for the possible calibration of sensors for relative humidity measurement. Experiment was designed as an isothermal expansion of the air. Although results are in good agreement with theory, experimental aparature is impropriety for the calibration for following reason:

- During the expansion, intake of the air to the pressure vessel was observed.
- Saturation of the air in the vessel was complicated and the level of saturation was established using calibrated sensor. Due to the fact that for the calibration one calibrated sensor was needed anyway and therefore additional calibration from external firm will be necessary.
- If the air was saturated at the level of 100% of relative humidity water in liquid state was secreted in the vessel.

For the calibration of the relative humidity sensors another methodes will be tested in the future.

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Nomenclature

Symbol	Dimension	Meaning
c	$(J{\cdot}(kg \cdot K)^{-1})$	Specific heat constant
E	(V)	Voltage
M	$(kg \cdot kmol^{-1})$	Molecular weight
n	(1)	number of degree of freedom
p	(kPa)	Pressure
r	$(J \cdot (kg \cdot K)^{-1})$	Specific gas constant
R	$(J \cdot (kmol \cdot K)^{-1})$	Universal gas constant
t	(s)	Time
T	(^oC)	Temperature
x	(1)	Specific humidity
φ	(1)	Relative humidity
κ	(1)	Poisson constant
ρ	$(kg \cdot m^{-3})$	Density

Indexes

Symbol	Meaning
da	Dry air
ma	Moist air
p	Constant pressure
v	Constant volume
wv	Water vapor

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