DEVELOPMENT OF A MEASURING SYSTEM FOR DETERMINING THE AIR DENSITY CORRECTION FACTOR FOR IONIZATION CHAMBERS OPEN TO THE ATMOSPHERE

by

Miloš V. DJALETIĆ

Department of Radiation and Environmental Protection, Vinča Institute of Nuclear Sciences, National Institute of the Republic of Serbia, University of Belgrade, Belgrade, Serbia

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This paper introduces a measuring system designed to determine the air density correction factor for ionization chambers open to the atmosphere. The system is intended for use in clinical and radiotherapy facilities, secondary standard dosimetry laboratories, and other settings where open-to-the-air ionization chambers are commonly utilized. While there are numerous universal and laboratory-grade instruments available for measuring relative humidity, air pressure, and ambient temperature, integrated systems that can measure these parameters and calculate and display the air density correction factor are rare, particularly in the domestic market in Serbia. This paper details the developed hardware, including specifications for the sensors used, as well as the software developed for microcontrollers and personal computers. Measurement results and simplified measurement uncertainty budgets are also presented and discussed.

Key words: ionization chamber, dosimetry, air density, air temperature, atmospheric pressure, correction factor, calibration, sensor

INTRODUCTION

Measuring ambient environmental parameters such as air pressure, temperature, and relative air humidity is of great importance in various fields, especially meteorology, industry, and metrology. In this paper, the emphasis is on the measurement of ambient conditions in the secondary standard dosimetry laboratory (SSDL) for the calibration of dosimeters in quantities such as air kerma, absorbed dose, ambient and personal dose equivalents, and others. In the laboratory, ionization chambers open to the atmosphere are used as secondary standards, which practically means that the inside of the chamber is filled with air of the same properties as the atmosphere surrounding the chamber [1, 2]. Measuring the ambient environmental parameters, especially the temperature and pressure near the chamber, defines the characteristics of the gas properties inside the chamber. Measurement of these parameters is of crucial importance for dosimetry because air pressure, ambient temperature, and, to some extent, relative air humidity [3] affect the air density inside the chamber. By introducing the air density correction factor k_d to account for this dependence is acounted for. The influence of the air density is well described in the literature [1, 2], and examined in scientific papers [3, 4]. Relevant international guidelines for dosimeter calibration list it as an influential quantity and provide instructions for its correction [5, 6]. There is a large selection of universal and laboratory-grade equipment in the market for measuring ambient temperature, air pressure, and relative humidity, from instruments that measure only one quantity to integrated systems for measuring multiple quantities. However, the prices of the systems are usually high, in the order of several thousand dollars.

This work aimed to design a domestic specialized integrated system that would measure the mentioned ambient parameters using modern sensors with good measurement characteristics according to the application at a favorable cost. The paper describes a measuring system, a MeteoKd software calculating the ambient parameters of the environment and determining the air density correction factor developed by the author for measurements in an SSDL. Its application can be found in clinical and radiotherapy facilities, as well as in other places where ionization chambers open to the atmosphere are used [1, 5, 6]. The paper also describes the used sensors and their characteristics. In the metrology laboratory for pressure, the

* Corresponding author, e-mail: djaletic@vin.bg.ac.rs

calibration process for pressure sensors is explained. In addition to the device, the author also developed accompanying software, which allows the measuring system to connect to a computer. The measurement results can then be graphically presented and saved for later use and processing. Besides, supplementary software was created to collect data from the digital multimeter during the testing process. The results of the calibration and testing of the measuring system are presented in the paper. The measurement uncertainty budget for individual parts and the whole system was estimated, as it is an important indicator of measurement accuracy.

IONIZATION CHAMBERS OPEN TO AIR

Ionization chambers are one of the oldest and most widespread gas-filled types of ionizing radiation detectors, having the simplest construction. In this paper, the focus will be on open-to-air (vented) cavity ionization chambers. These types of chambers are used as standards in SSDL. The vented cavity ionization chamber consists of a wall usually made of graphite or a special plastic (most used is polyoxymethylene) as one electrode and an air-filled cavity with a collecting electrode in its center. If the wall is made of a nonconductive material (plastic), its inner surface must be lined with a thin conductive graphite coating and can be used as an electrode [1, 2]. The cavity volume, open to the surrounding atmosphere through a venting hole, ensures that the air inside has the same properties (pressure, humidity, and temperature) as the surrounding atmosphere.

Working principle

During the passage of ionizing radiation through the active volume of the chamber, gas molecules are ionized (air in this case). When a neutral gas molecule is ionized, an ion pair is created – a positive ion and a free electron. Ions are formed by the direct interaction of incident radiation with gas or by secondary processes of charge transfer in the gas, during which part of the energy of incident radiation can cause the ejection of electrons. Of interest is the total number of electron pairs created along the trajectory of the primary photon beam. To ionize the gas, the energy of the incident photon (in the general case of the incident particle) must be higher than the ionization energy of that gas, which is usually from 25 eV to 35 eV per ion pair. Since the ionization takes place in the electric field established within the active volume of the ionization chamber, separation and accumulation of positive and negative charges on the electrodes of the chamber occur (wall and center electrode). This build-up of charge causes a current to flow between the chamber electrodes in the order of pA or nA. As this current is very low, during the construction of the ionization chambers, the leakage current of the insulator that isolates the electrodes is also taken into account. The insulator should be polished and free of defects to prevent the accumulation of moisture, which would increase the leakage current. One pole of the power supply for polarization is fed to the electrode formed by the inside surface of the chamber wall. The other pole is connected to the *guard* ring between the insulators that separate the chamber wall from the central electrode. An electrometer circuit links the central electrode to a *guard* ring. As the voltage between the central electrode and the *guard* ring is small, the leakage current between them is negligible. This principle is also used with the triaxial cable to avoid signal degradation. As the leakage current is negligible (on the order of fA), the strength of the current registered by the electrometer circuit depends only on the amount of accumulated charge on the electrodes of the chamber. The bias voltage depends on the construction of the chamber and is usually between 200 V and 400 V [1, 2].

MATERIALS AND METHODS

Correction for influence quantities and air kerma

The amount of charge generated (by ionizing radiation) inside the vented ionization chamber is influenced by the air density and water vapor content inside it. To account for this dependency, measurement results are normalized to the reference conditions, which are: air temperature T_{ref} = 293.15 K (20 °C), air pressure P_{ref} = 1013.25 hPa, and relative humidity h_{ref} = 50 %. When measurements are taken under different conditions than the reference, an air density correction factor k_d must be used. Air density is one of the influence quantities since it directly affects the measurement results.

Air density correction factor k_d

$$k_d = k_T k_p = \frac{T_{amb}}{T_{ref}} \frac{P_{ref}}{P_{atm}} \tag{1}$$

where T_{amb} is the ambient air temperature near the ionization chamber expressed in degrees Kelvin and P_{atm} – the atmospheric pressure expressed in hPa near and at the same height as the ionization chamber [4-6].

The air density correction factor k_d increases by approximately 1 % for every 3 °C increase in temperature and decreases by approximately 1 % for every 10 hPa drop in air pressure.

The value of the calibration coefficient N_k for the conversion of the amount of charge into air kerma is always expressed at the standard temperature T_{ref}, pressure P_{ref}, and relative humidity of 50 %. Therefore, it is necessary to apply the appropriate correction factors. The measured air kerma K_a with applied air density k_d and relative humidity k_h correction is

$$K_a = QN_k k_d k_h k_i \tag{2}$$

where Q represents the measured charge generated inside the chamber, N_k – the air kerma calibration coefficient of the chamber, and k_i – the correction factor for other influence quantities (*e.g.*, chamber response to the applied voltage polarity k_{pol}, incomplete charge collection efficiency of the employed ionization chamber mainly due to the ion recombination processes k_s, and others). The same expression applies to other dosimetric quantities (*e. g.*, absorbed dose), just the other calibration coefficients are used for different quantities.

In this way, the provided result is the real value of kerma in the air, independent of the values of the influence quantities (T_{amb} and P_{atm}, in particular). Air relative humidity k_h is also an influencing factor, but its maximum effect is up to 0.4 % over its entire range typically encountered in laboratory conditions (30 % to 70 %), so a correction can usually be omitted and just accounted for in the measurement uncertainty budget [3-6].

MeteoKd SYSTEM OVERVIEW

The system has a central unit and four temperature probes. A block diagram of the whole system hardware is given in fig. 1. The central unit is powered by a PC USB port or power bank (standalone mode). A additional power source is connected to the central unit to provide energy for the optoisolated temperature probes. Optoisolation protects the central unit and PC from ground loops, noise, and voltage surge spikes that might occur in the long cables connecting the temperature probes. The microcontroller in the central unit manages the user interface, processes data, collects sensor data from the central unit, communicates with the temperature probes, and handles USB communication with the PC when connected.

Sensors

The atmospheric pressure sensor used in the central unit is LPS33HW, manufactured by STMicroelectronics. It features a measurement range of 260 hPa to 1260 hPa, a 24-bit resolution, and automatic temperature compensation. The sensor has a relative accuracy of ±0.1 hPa within the 800 hPa to 1100 hPa range and a long-term stability of ±1 hPa per year. Absolute accuracy with one-point calibration is ±1 hPa or better when a proper laboratory calibration is performed [7].

The relative humidity sensor used in the central unit is HTU31D, manufactured by TE Connectivity Sensors. It has a measurement range from 0 % to 100 % with a 0.01 % resolution and ±2 % accuracy. Its long-term stability is better than 0.25 % per year [8].

The precision temperature sensor used in the temperature probe is TMP117, manufactured by Texas Instruments. The measurement range is from –55 °C to 150 °C with a typical accuracy of ±0.05 °C in the range from –20 °C to 50 °C and ±0.1 °C with a factory calibration. This range exceeds the intended use of this probe for metrology purposes. Resolution is 7.8125 m°C per bit, and long-term stability is ±0.03 °C per 1000 hours at 150 °C. This sensor was selected because it has excellent absolute accuracy and is 100 % factory tested on a production setup that is NIST traceable and verified with equipment that is calibrated to ISO/IEC 17025 accredited standards [9].

Central unit

The central unit is the core component of the system. It houses all the necessary hardware for processing and communication, as well as sensors for atmospheric pressure and relative humidity. The user interface consists of a two-line backlit alphanumerical liquid crystal display, four push buttons for menu navi-

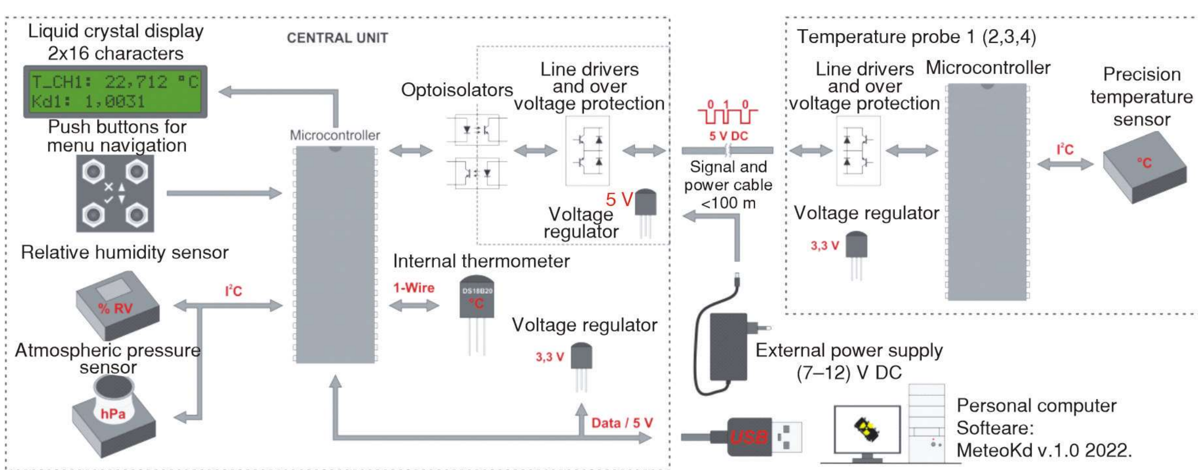

Figure 1. System hardware overview

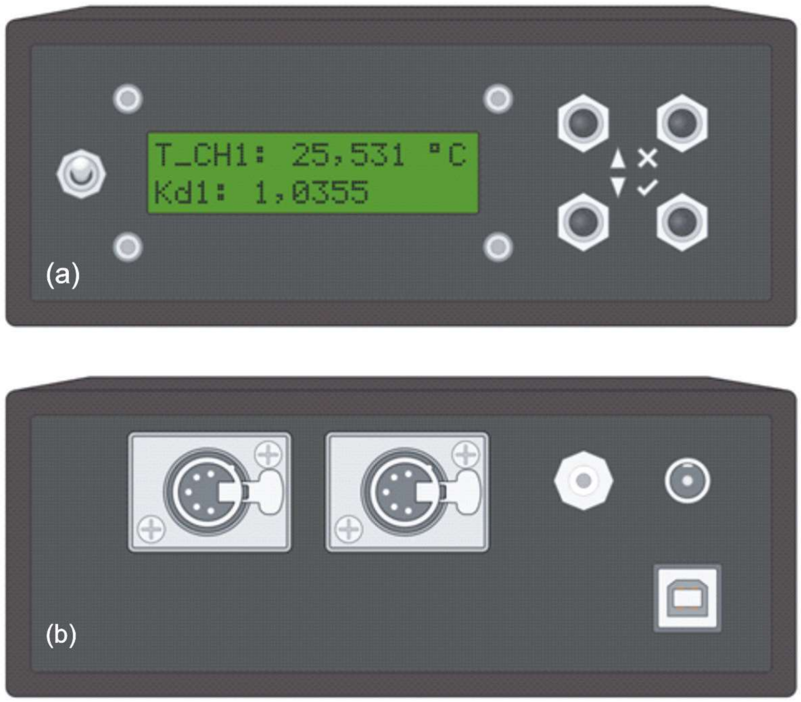

Figure 2. Central unit front side with user interface (a) and backside with temperature probe connectors, air inlet, DC power connector, and USB connector (b)

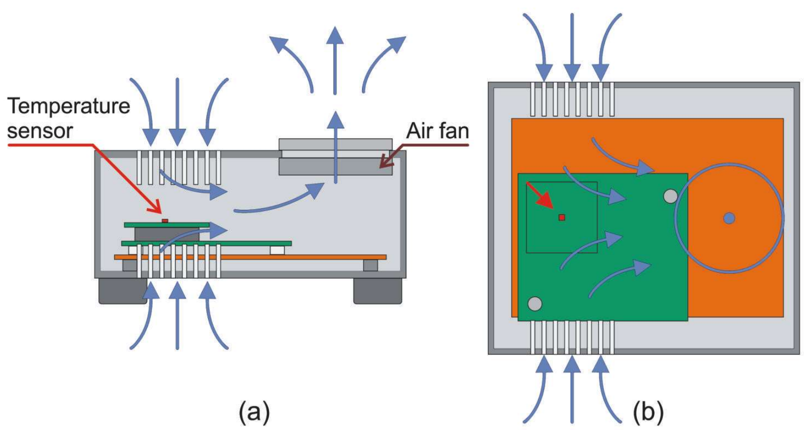

Figure 3. Temperature probe enclosure cross-section; air path diagram with position of temperature sensor and air fan side view (a) and top view (b)

gation, and a toggle power switch on the front side fig. 2(a). On the back side, there are two XLR connectors for remote temperature probes, an atmospheric pressure sensor air inlet, a DC power connector, and a Universal Serial Bus (USB) connector for communication with a personal computer fig. 2(b), from left to right.

Temperature probe

The temperature probe is designed around a precision temperature sensor that measures ambient air temperature. Special attention was paid to the probe's internal design so that the sensor self-heating and surrounding components producing heat have minimal effect on the measurement. This was achieved by using an air fan and arranging the other electronic components on the printed circuit board suitably. The air fan also helps the sensor package achieve faster temperature equilibrium with the surrounding ambient air temperature, thus providing a faster measurement response time. Ambient air is sucked in through probe enclosure slits, and after passing over the temperature sensor is released out of the enclosure through an air fan, fig. 3. This way, the air fan is not affecting the air temperature. The cable length for connecting the probe to the central unit is usually ten to twenty meters, but it can be up to 100 meters or more, depen ding on the application. The used cable is shielded for improved electrical noise immunity. Two probes can be connected to one cable (LIYCY 6×0.14 mm^2 or LIYCY 6×0.25 mm^2, for longer distances) since one probe uses two wires for power and one for bidirectional communication. The air fan is powered by 5 V directly from the cable, but the microcontroller and the sensor are powered by 3.3 V provided by a local voltage regulator for better voltage stability and regulation. The data line is protected from overvoltage peaks by a transient voltage suppression (TVS) diode.

SOFTWARE

This device can be used as a standalone instrument or can be connected to a PC. When powered, a series of tests are performed. The liquid crystal display (LCD) is tested by turning all the pixels on, an external power supply for the temperature probes is checked, and if present, probe initialization follows. All four channels are checked for the presence of a temperature probe. If the initialization is successful, a message is displayed on the LCD.

In standalone mode, atmospheric pressure is measured first, and the result is shown on the LCD. A value of the temperature probe measurement and calculated k_d value are shown for every initialized probe. Then, relative air humidity is measured and shown, after which atmospheric pressure is measured again. This process repeats indefinitely until a button is pressed.

The PC software – MeteoKd

In PC mode, the device communicates with the PC running the MeteoKd software, developed especially for this purpose. The measurement process is the same as in standalone mode, except for the measurement results, transferred to the software for numerical and graphical representation.

The user interface is intuitive. In the upper left part, there is a status indicator that shows if the device is connected. Below is the text box for entering the sampling interval along with the start and stop buttons. Further down, there are four text boxes labeled "T1", "T2", "T3", and "T4", displaying measurements from the temperature probes. Next, there is a text box showing the air pressure value, followed by four calculated air density correction factors for each temperature probe labeled "Kd1", "Kd2", "Kd3", and "Kd4". Finally, there are text boxes for air relative humidity and internal temperature values. On the right side, tables display all the data acquired from sensors and calculated air density values, with time and date in the rightmost column, fig. 4.

In the lower left part of the window, there is a list of temperature probes ("CH1", "CH2", "CH3", "CH4") and a "Graph" button. After selecting the desired channel and pressing the button, a graph is displayed in place of the tables, fig. 5. On the graph, there are three lines: red for temperature, blue for pressure, and green for calculated air density k_d. By clicking the left mouse button, a vertical marker line appears, and measured values for the selected point are displayed in blue below the graph. After each sample, the data is automatically saved to the PC storage location for further processing and archiving.

The developed computer software enabled the automated collection of a large number of measurements during calibration and testing. Without this automation, it would have been impossible to read and process such a vast amount of synchronized measurement. The graphic display of measured values is particularly useful during calibration, as it allows the metrologist to continuously monitor changes in ambient temperature and air pressure.

CALIBRATION

Temperature probe sensor

All TMP117 temperature sensors are factory-calibrated and verified during production. The used calibration equipment has traceability to the NIST (National Institute of Standards and Technology, Gaithersburg, Maryland, United States) and is calibrated to the ISO/IEC 17025 accredited standards, as specified in the sensor's technical specification. No additional calibration was performed since the ±0.1 °C factory calibration accuracy is sufficient for this application [9].

Pressure sensor calibration

Pressure sensor calibration was performed since the factory calibration accuracy of 2.5 hPa was insufficient. Calibration was performed in an accredited metrological laboratory specializing in the calibration of pressure gauges, The Laboratory for Thermal Engineering and Energy at Vinča Institute of Nuclear Sciences. The results of the calibration are shown in tab 1.

The mean value of the deviation Δp_s is –0.285 hPa. Applying this offset calibration value ($p - \Delta p_s$), the maximum deviation of the offset-corrected value Δp_m is 0.063 hPa. The conservatively estimated value of the standard measurement uncertainty of the calibration is determined as the root of the sum of the square of the maximum deviation Δp_m and half of the maximum value of the extended measurement uncertainty of comparison with the standard, *i. e.*, $[(0.063 \text{ hPa})^2 + (0.5 \cdot 0.088 \text{ hPa})^2]^{0.5} = 0.077$ hPa.

ATMOSPHERIC PRESSURE AND AMBIENT TEMPERATURE COMPARISON

In the calibration laboratory of the Radiation and Environmental Protection Department at Vinča Institute of Nuclear Sciences, two systems are used for measuring atmospheric pressure and ambient temperature. The first consists of an analog aneroid barometer and a Keithley 2700 digital multimeter with platinum resistance elements (Pt100) as probes, while the second system is an integrated solution from Titon – Env-Coll 2012 2T with multiple sensors, shown in fig. 6 (barometer, hygrometer, and two temperature probes with platinum resistance elements Pt1000). Keithley 2700 digital multimeter and Titon Env-Coll 2012 2T integrated measuring system were used for comparison. The aneroid barometer was

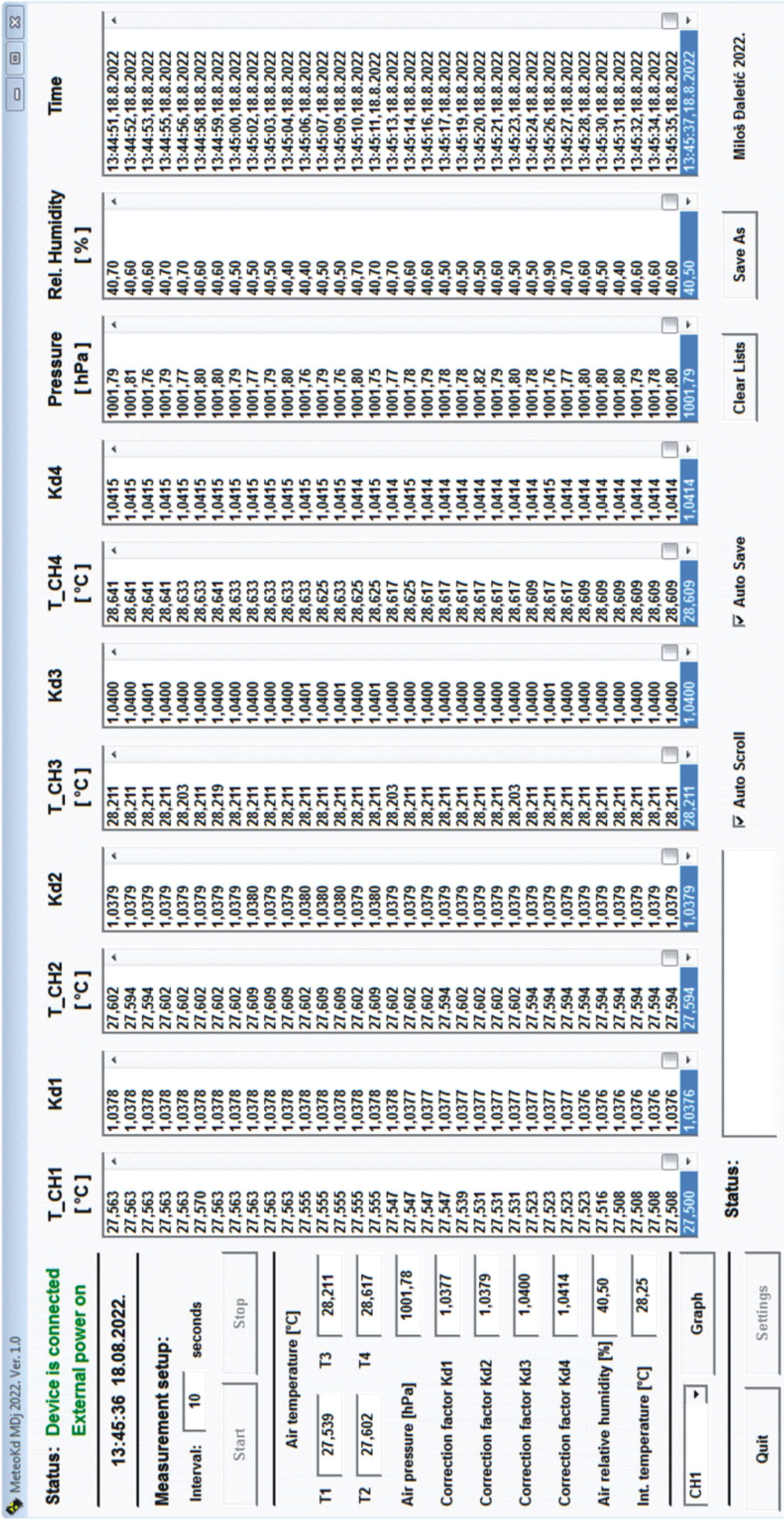

Figure 4. MeteoKd PC software – view of the tables with measured data

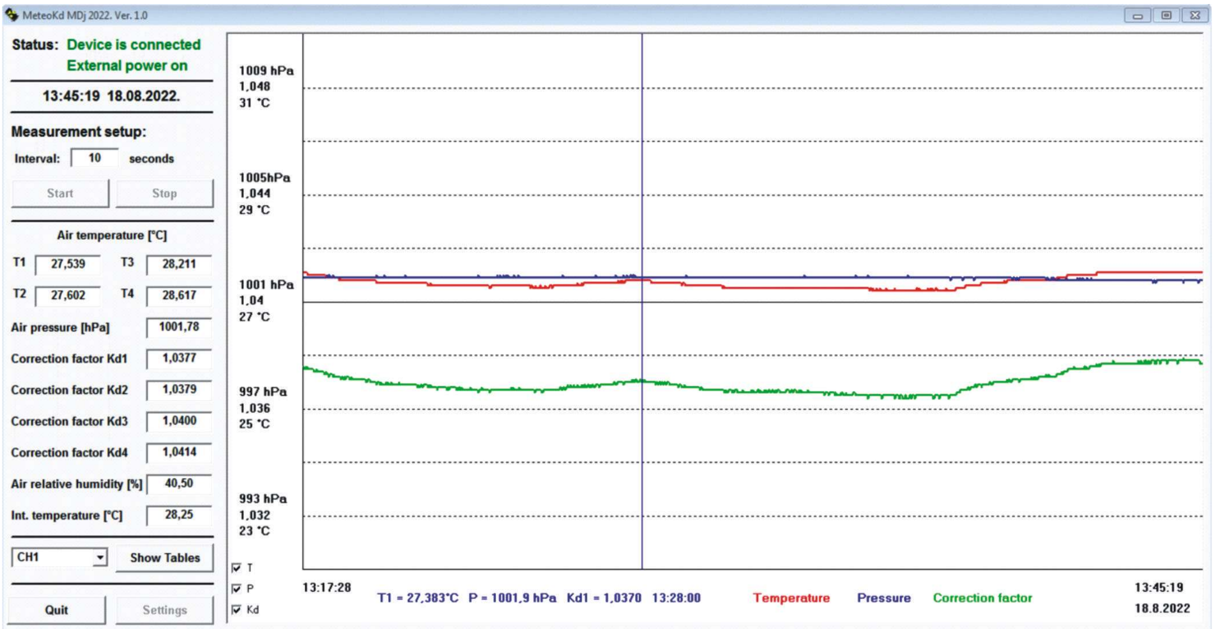

Figure 5. MeteoKd PC software – view of the graph with measured data from a selected probe

Table 1. Pressure sensor calibration results

Reference standard pressure, p_e [hPa]	The mean value of the sensor readings, p [hPa]	Deviation, Δp [hPa]	Hysteresis, h [hPa]	Extended measurement uncertainty, k = 2, U [hPa]
1048.674	1048.429	–0.245	0.048	0.086
1030.638	1030.383	–0.256	0.059	0.088
1005.764	1005.510	–0.255	0.037	0.082
994.755	994.462	–0.294	0.065	0.087
979.028	978.712	–0.316	0.048	0.083
962.328	961.987	–0.341	0.034	0.080

Figure 6. Env-Coll 2012 2T measuring system with a probe for measuring the relative humidity of air (left) and MeteoKd (right) with external power supply during testing

not used due to insufficient accuracy. All the listed devices are calibrated in accredited laboratories with secondary or working standards that are traceable to primary standards.

Keithley 2700 digital multimeter with Pt100 probes

This instrument has a resolution of 0.001 °C [10] and an accuracy of 0.01 °C ±0.06 °C, according to the calibration certificate. The estimated expanded measurement uncertainty of this system is 0.1 °C. The author developed simple PC software for data acquisition automation for this multimeter using the RS232 interface.

Integrated meter of ambient parameters Env-Coll 2012 2T

The Env-Coll 2012 2T, manufactured by Titon Bt., is an ambient parameters measurement system. It has two Pt1000 temperature probes, a relative air humidity meter, and an air pressure meter. It connects to a personal computer via a USB connection, without a standalone mode of operation. This device can calculate the correction factor for air density k_d. Measurement capabilities, according to the manufacturer's specifications, are temperature measurement range from –5 °C to 60 °C; accuracy of temperature measurement: 0.03 °C (for the whole range), 0.01 °C (in the 15 °C to 35 °C range); air pressure measurement from 900 hPa to 1100 hPa, accuracy 0.3 hPa; measurement of relative air humidity from 10 % to 90 % with 2 % accuracy [11]. The device comes with software for displaying and logging measured values. According to the certificate of calibration of the temperature probe T1, the mean deviation from the standard measurement is –0.25 °C within the specified range of 20 °C to 30 °C. The expanded measurement uncertainty ($k = 2$) is 0.26 °C. Considering the large measurement uncertainty of calibration, and based on previous calibrations, the estimated uncertainty is 0.1 °C. According to the air pressure sensor calibration certificate, the deviation from the reference value is –0.837 hPa at a pressure of 997.705 hPa, with an expanded measurement uncertainty ($k = 2$) of 0.092 hPa.

Measurement set-up

An extruded polystyrene board was placed on the calibration bench in the X-ray calibration room. The probes of the MeteoKd device are placed on the extruded polystyrene board, while the Pt probes of the Env-Coll and Keithley instruments were placed on supports and were free in the air, above the board at the height of the probe enclosure slits of the MeteoKd device, fig. 7.

The atmospheric pressure test setup is shown in fig. 8. A syringe was used to set the atmospheric pressure. A screw was then employed to fine-tune and secure the piston's displacement, thereby precisely adjusting the pressure value. The syringe was connected to a *T* connector via a hose, with the pressure inlets of both devices also attached to the connector.

Throughout the testing, the devices were connected to a laptop computer equipped with the appropriate data acquisition software. All measurements were carried out in the calibration laboratory of the Radiation and Environmental Protection Department at Vinča Institute of Nuclear Sciences.

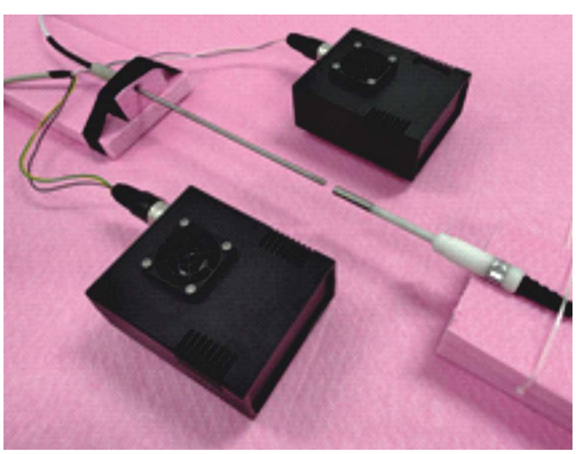

Figure 7. Measurement set-up for ambient temperature measurement

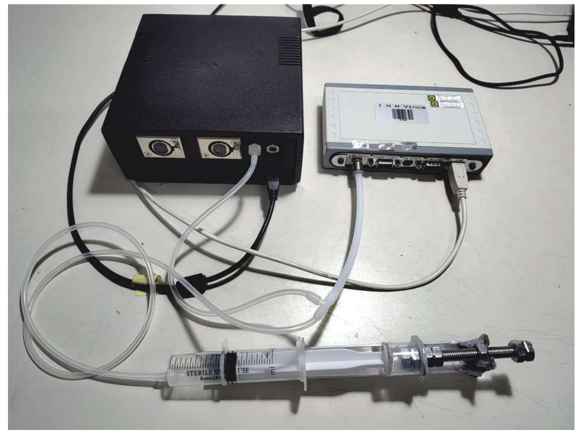

Figure 8. Measurement set-up for air pressure measurement

MEASUREMENT UNCERTAINTY

The uncertainty in ambient pressure measurement is 0.586 hPa or 0.061 % as a relative combined uncertainty ($k = 2$) at the lowest expected pressure of 960 hPa representing the worst-case scenario. For ambient temperature measurement, the uncertainty is 0.061 °C, or 0.021 % as a relative combined uncertainty ($k = 2$) at the lowest expected temperature of 291.15 K, also representing the worst-case scenario.

Relative combined uncertainty ($k = 2$) of the air density correction factor kd calculated based on these measurements is 0.095 %, with included ±0.2 °C temperature variation and ±0.2 hPa pressure variation at extreme allowed laboratory ambient conditions (291,15 K and 960 hPa).

Both temperature and pressure sensor measurement characteristics comply with guidelines stated in the IAEA Human Health Series No. 44, Establishing a Secondary Standards Dosimetry Laboratory [12] which states: a barometer with a 0.5 hPa resolution and better than 0.1 % calibration uncertainty; and a thermometer with a 0.2 °C resolution.

Chamber calibration factor N_k uncertainty is usually from 0.8 % to 1.3 % ($k = 2$), and it is a major uncertainty contributor. Air density correction factor k_d contribution is 0.095 %, approximately an order of magnitude lower than chamber calibration factor uncertainty.

By comparing tab. 2 and tab. 3, the dominant influence on the measurement uncertainty is the calibration factor of the ionization chamber. The measurement uncertainty of the correction factor k_d depends on several factors, so it is possible to use instruments with a lower accuracy class than those currently used in the laboratory to measure ambient temperature and air pressure.

The measurement uncertainty of the calibration factor of the ionization chamber being calibrated, obtained using existing measuring instruments, is comparable to and negligibly higher than when using the MeteoKd device (0.86 % compared to 0.84 %). This confirms the feasibility of using the MeteoKd device

Table 2. Simplified air kerma measurement uncertainty budget when laboratory instruments are used (Keithley 2700 and aneroid barometer)

Uncertainty source	Relative error [%]	Coverage factor	Sensitivity	Relative standard error [%]
Chamber calibration factor N_k	0.8	2	1	0.4
Temperature	0.13	1.73	1	0.076
Pressure	0.11	1.73	1	0.064
Source distance	0.1	1.73	2	0.058
Combined measurement uncertainty (coverage factor k = 1)				0.43
Combined measurement uncertainty (coverage factor k = 2)				0.86

for measuring ambient parameters and determining the correction factor for air density k_d in metrological laboratories and other relevant facilities.

RESULTS AND DISCUSSION

Pressure measurement

Measurements were taken every two seconds. For each measurement point displayed on the graph in fig. 9, the mean value of thirty measurements was used. The results from the Env-Coll 2012 2T device were taken as references and corrected according to the calibration certificate. The results of the MeteoKd device were corrected according to the offset value obtained from calibration in the metrological laboratory for the calibration of pressure gauges, Laboratory for Thermal Engineering and Energy at Vinča Institute of Nuclear Sciences. The estimated measurement uncertainty of the MeteoKd device is 0.6 hPa, while Env-Coll 2012 2T device, according to the manufacturer's technical specifications, has an uncertainty of 0.3 hPa. The difference in readings between the devices ($P_m - P_{ref}$) is less than ±0.2 hPa which is within the measurement uncertainties of both devices. Given that there are no significant deviations, the results are satisfactory for this type of application.

Table 3. Simplified air kerma measurement uncertainty budget

Uncertainty source	Relative error [%]	Coverage factor	Sensitivity	Relative standard error [%]
Chamber calibration factor N_k	0.8	2	1	0.4
Calculated k_d	0.095	1.73	1	0.055
Source distance	0.1	1.73	2	0.058
Combined measurement uncertainty (coverage factor k = 1)				0.42
Combined measurement uncertainty (coverage factor k = 2)				0.84

Temperature measurement

Measurements were performed in the still atmosphere of the calibration room. Probes were far from other objects on all sides. To minimize the influence of temperature gradients, the probes were positioned away from other objects on all sides, except for the bottom. The bottom side was supported by an extruded polystyrene board, chosen for its low thermal mass and conductivity. The measurement uncertainty of the device is MeteoKd: 0.061 °C; Keithley 2700 with Pt100 probe: 0.1 °C; Env-Coll 2012 2T with Pt1000 probe: estimated 0.1 °C, according to manufacturer specification: 0.01 °C. The mutual deviation of the measured values does not differ by more than 0.05 °C, which is shown in the graph, fig. 10. The Env-Coll 2012 2T Pt1000 probe exhibited a slower response as the room temperature started to rise, because of its higher thermal mass compared to other probes. The dynamic responses of all three systems will be investigated in future studies. Because the effect is minimal, it does not significantly impact metrology, as calibration measurements are conducted in a stable temperature atmosphere. Also, ionization chambers, especially the large volume ones (1 l and 10 l), have a delay in the inside air temperature change concerning the surrounding air temperature, which will also be a subject of further studies since it directly affects the k_d. The results are satisfactory about the purpose of the developed device.

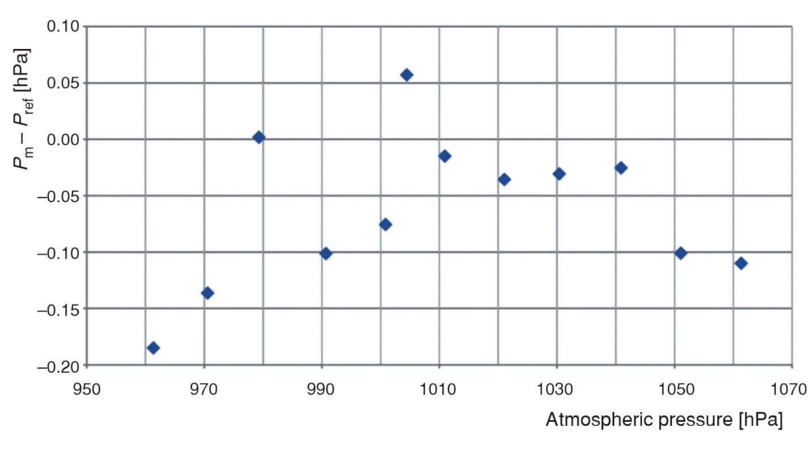

Figure 9. Deviation of measured atmospheric pressure with the developed system and a reference system

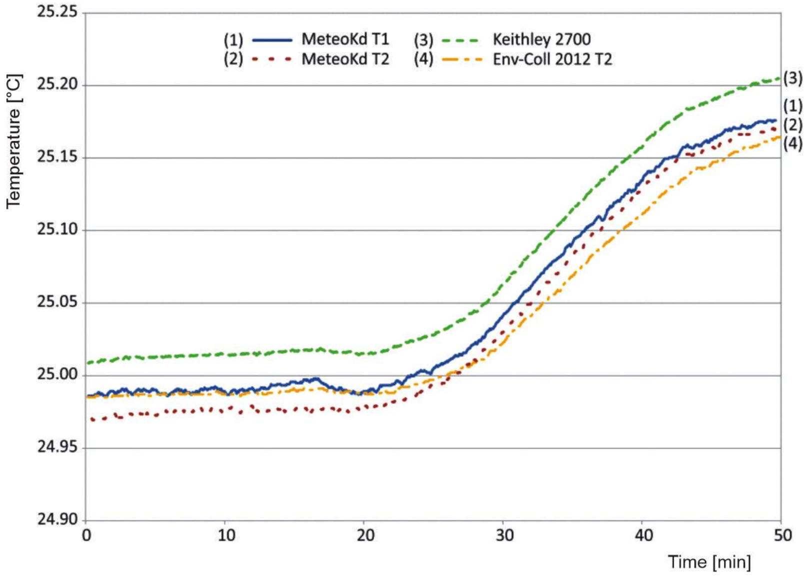

Figure 10. Comparison of ambient air temperature measurement using three tested instruments

CONCLUSIONS

The MeteoKd system, designed to measure environmental atmospheric parameters, was developed and presented. Its measurement characteristics are comparable with much more expensive systems. The pressure sensor readings differ by ±0.2 hPa compared to a commercial device, which is within the measurement uncertainties of both systems. The temperature sensors were compared with two commercial devices used in SSDL, showing a deviation of no more than ±0.05 °C. The dynamic responses of the temperature sensors in all three systems will be investigated in future studies. The test results are satisfactory, comparable to the values of commercial systems, and meet the requirements for measurement accuracy.

The measurement uncertainty budget of the developed MeteoKd system was estimated and compared with the currently used commercial systems. The measurement uncertainty of the developed system is similar to that of the commercial systems currently in use. Further verification of the system includes a more detailed examination of the temperature probes and monitoring of the long-term stability of the entire system.

The presented system is a good starting platform that can be modified, *e. g*., by replacing or adding different sensors in the measuring unit or probe, and it can be adapted to other purposes as needed, especially for meteorology. Following additional testing and verification, MeteoKd could be commercially utilized in metrology laboratories for calibrating dosimeters, in clinical and radiotherapy facilities, and in other settings where ionization chambers open to the atmosphere are used, as the results obtained thus far have been satisfactory.

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AUTHOR STATEMENT

The author designed and created the essential hardware and software for this device as part of his practical work for his master's vocational studies final thesis. He personally funded the development and production of the device prototype.

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Милош В. ЂАЛЕТИЋ

РАЗВОЈ МЕРНОГ СИСТЕМА ЗА ОДРЕЂИВАЊЕ КОРЕКЦИОНОГ ФАКТОРА ГУСТИНЕ ВАЗДУХА ЗА ЈОНИЗАЦИОНЕ КОМОРЕ ОТВОРЕНЕ КА АТМОСФЕРИ

У раду је приказан развој мерног система за одређивање фактора корекције густине ваздуха за јонизационе коморе отворене ка атмосфери. Систем је намењен употреби у клиничким и радиотерапијским установама, секундарним стандардним дозиметријским лабораторијама и на другим местима где се користе јонизационе коморе које су отворене ка атмосфери. На домаћем тржишту постоји мноштво инструмената за мерење релативне влажности, ваздушног притиска и температуре околине, али недостаје интегрисани систем који може да мери све ове параметре, као и да израчуна и прикаже фактор корекције густине ваздуха. Приказан је развијен хардвер са спецификацијама коришћених сензора, уз развијени софтвер за микроконтролер и персонални рачунар. Приказани су и анализирани резултати мерења и поједностављен буџет мерне несигурности.

Кључне речи: јонизациона комора, дозиметрија, густина ваздуха, температура ваздуха, ваздушни притисак, корекциони фактор, еталонирање, сензор