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CALCULATION OF VENTURI NOZZLES DIAMETER FOR NASAL BREATHING EVALUATION DEVICE

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ABSTRACT

Nozzles and Venturi nozzles are devices that are inserted in circular cross-section conduit to create pressure difference of static pressure. Based on that pressure difference, flow rate of flowing fluid can be calculated. Methodology results of Venturi nozzle diameter calculating device to determine the pressure drop/flow rate characteristics of the human nasal airways are described. The results of our method offer high-stability performance and compact construction. The standard studying and metrological verification pointed on a possibility of obtaining sufficiently reliable measurement results when using a flow meter based on a Venturi nozzle. This method can be considered as a respect to improvement information-measurement technology alternative control and technical diagnostics. In combination with a computer interface, these devices provide a high level of mobility and open up entirely new perspectives for rhinological research and practice, especially in human physiology and environmental studies.

KEYWORDS: Rhinomanometery, Pneumotachography, Flow Meters, Pressure Sensors, Venturi Nozzle, Pressure Drop and Flow Rate

INTRODUCTION

Three types of nozzles are covered in calculator: ISA 1932 nozzle, long radius nozzle and Venturi nozzle. All three types differ from each other based on its shape. All nozzles have radius shaped convergent inlet with cylindrical throat and Venturi nozzle also has divergent part as outlet. Nozzle and Venturi nozzle calculator can be used for both liquids and gases. In medical applications the human respiratory system can be represented as an analog pneumatic actuator, including a power source device for air suction and discharge, and a pneumatic system of air pipeline with resistance on airflow path, through nasal passages or human mouth. This power source includes the actuator muscles for the human lung, which function as a compressor with a cycle in suction and in discharge, as well as the nasal passage and oral cavity, which are considered as pipelines with resistances.

At present, medical devices have been presented for nasal breathing diagnosis[1], which are based on analysis of pneumatic air resistance in coordinates of «flow rate-pressure» (actual pressure drop) [2], coinciding with hydraulic analysis and pneumatic resistance on hydraulics industrial and pneumatics by designing and studying various hydro-pneumatic devices.

STATEMENT OF THE PROBLEM

Venturi devices use differential pressure to create a vacuum within the device, which allows users to take advantage of the suction to mix two fluids. As one liquid flows through the Venturi device, higher entry pressure and lower exit pressure, combined with a narrow point on the injector tube, create a vacuum. This is known as the Venturi effect. A suction port on the side of the device near the vacuum point allows another liquid to be drawn into the first one. Once the different pressures, as well as the rate of air flow, are known, the amount of suction the Venturi device creates can be calculated.In order to construct and design a base for a local diagnostic device, the flow rate characteristics of human nasal passages were reviewed and the methodology of calculation of such a device was observed. So in this study we are able to measure the diameter of the Venturi device's outflow hole. And to measure the diameter at the narrower suction point, within the device.

THE MAIN PART

The analysis of current flow meter construction and pressure sensors that are used to determine the pressure drop-flow rate characteristics for any pneumatic resistance indicates the technical possibilities of a modern automatic processing measuring techniques for information receiving, and the possibility of using flow meter devices such as the Venturi nozzle as measuring equipment [3-5]. Figure 1 shows a semi-construction diagram of the device used for determining the flow rate by using a Venturi nozzle, as in unit1, we constructed a hole2 diameter d, hole 3, and a differential pressure sensor type PS1 with analog output, which was used to measure pressure drop. Tube3 with a supply «-» sensors PS1 corresponds to discharge measuring (vacuum) in the pipeline, and the channel «+» allows us to obtain the value of the pressure drop.

Thus, to Calculate the Diameter of the Venturi Nozzle, it is Necessary to Collate the Following Data and Limitations

- The maximum flow rate that is generated by human inspiration must not be greater than $Q_{макс} \leq$ 8 L/s and in expiration $Q_{макс} \leq$ 16 L/s [6]. According to health state, age, and nasal passages disease, inspiration cannot even reach 4…6 L/s;
- Using a nozzle diameter less than the $d \leq$ 7 mm leads to a significant difficulty of patient during inspiration, especially at high-intensity mode frequency and amplitude;
- Sensors that we used to measure pressure drop must be in full-scale range (when reaching the maximum flow rate generated by humans), with the optimal range of up to 2/3 of the maximum scale value, in order to improve accuracy of measurements;
- When using the Venturi nozzle, one should take into account the irreversibility of this device, which means that the flow rate measurement is possible only when the air flow is in the direction of the «nozzle-diffuser», and not vice versa;
- The maximum pressure developed by the flow of air passing through the nozzle should not exceed human physiological possibilities (accurately, its muscular possibilities as a lungs actuator for generating a cycle of expansion and contraction).
- The last limitation is based on preliminary static measurements of human possibilities to create excessive pressure in the expiratory cycle and a negative one (vacuum) in the inspiratory cycle, as carried out in Kharkiv National University of Radio Electronics. The pressure gauge was used together with mono-vacuum meter type MVM4-УУ2 by Ukraine State Standard2405 with a diameter of 160 mm of the scale:
- From 0 to 0.6 kilogauss / cm2 and a scale factor of 0.02 kilogauss / cm2 for excessive pressure measurement;
- From 0 to «minus» 1 kilogauss / cm2 and a scale factor 0.02 kilogauss / cm2 for discharge pressure measurement (vacuum).

During the measurements yield, a rubber tube with a length of 0.5 m was attached to the manometer, and the manometer was installed vertically at nose level. Air suction (inspiration) and discharge (expiration) were carried out through the mouth, when the free end of the tube picked in the mouth, because the process of suction and discharge was carried out in a closed space (lung, larynx, oral cavity, monovacuum meter).

According to Pascal's law, all measuring points of excessive pressure or discharge (vacuum) remain constant. As a result, **the following measurements were established**:

- The maximum excessive pressure is about 0.15 kilogauss / cm2 or ~15 kPa;
- The maximum vacuum value is about 0.4 kilogauss / cm2 or ~40 kPa.

The obtained results allow us to make a preliminary choice about the maximum values of the pressure transducer that is subjected to the limitation according to Item No. 5. This was considered as counter for the pressure generated by the flow meter due to the resistance of the air flow in its most narrow part, and this should not exceed 30% of the value generated by humans, which allow us to determine the maximum pressure value of the transducer at about 5 kPa in the expiratory cycle (excessive pressure) and 10 kPa in the inspiratory cycle (discharge or suction).

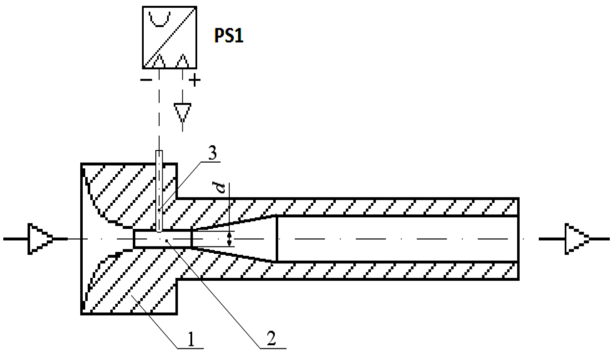

Figure 1: Semi-Construction Scheme Flow Meter, Built on the Principle of a Venturi Nozzle

The design of the diagnosing device considered the flow rate characteristics only for the air suction cycle. To measure the diameter of a Venturi nozzle, we used the flow rate calculating formulas [3]

$$Q = 10^3 \mu \varepsilon \varepsilon_c \frac{\pi d^2}{4} \sqrt{\frac{2 \cdot 10^3}{\rho_a} \Delta p_1} \text{ ,L/s,} \quad (1)$$

Where:

μ - The discharge coefficient of flow meter used in construction,

ε - Correction coefficient, taking into account the expansion of atmospheric air in the flow meter,

ε_c - Correction coefficient, taking into account the location of the flow meter,

d - Nozzle diameter, in mm,

ρ_a - Air density, kg / m3

Δp_1 - Pressure drop in pressure sensor PS1, with two measuring holes, one of them is for negative pressure measurement (vacuum or discharge) located in the nozzle diffuser and connected to an electrical outlet, and the second is communicated with atmosphere, and measured in kPa. The air density was determined by the following formula:

$$\rho_a = \frac{p_a}{R_a \cdot T_a} \approx \frac{p_a}{R_н \cdot (273.15 + t^\circ C)} \left[\frac{Pa}{\frac{J}{kg \cdot К} \cdot К} = \frac{N \cdot kg}{м^2 \cdot N \cdot м} = \frac{kg}{м^3} \right] = \frac{98.1 \cdot 10^3 p_a^1}{288 \cdot 735.6 \cdot (273.15 + t^\circ C)} = 0.463 \frac{p_a^1}{273.15 + t^\circ C}$$, кg/m3, (2)

Where:

p_a - Atmospheric pressure, in Pa, p_a^1 - Atmospheric pressure [mmHg], which is associated to pressure in [Pa] equality 98,1 • 103 = 735.6 mmHg column R_a - Gas constant at atmospheric pressure having a dimension $\left[\frac{J}{kg \cdot К} = \frac{N \cdot м}{kg \cdot К} \right]$, which assumes a constant for all changes in values of atmospheric pressure, equal to the value of the gas constant $R_н$ for normal atmospheric conditions by Ukraine State Standard 19862 - when air temperature $T_н =$ $20^\circ C$ and pressure $p_н =$ 101.325 kPa = (760 mm Hg column).

$$R_a \approx R_н = 288 \frac{J}{kg \cdot К},$$ (3)

$T_a = 273.15 + t^\circ C$ -Absolute temperature, measured in degrees Celsius [$^\circ C$] before testing.

Nomination of correction coefficients [3]:

for flow meter used in construction, recommended coefficient value 0f $\varepsilon_c = 1$;

coefficient value ε =1 accepted at a ratio of $\Delta p_1 \cdot \Delta \leq$ 2 kPa, and at $\Delta p_1 \cdot \Delta$ > 2 kPa that is calculated by the formula:

$$\varepsilon = 1 - \frac{3}{4 \cdot \chi} \cdot \frac{\Delta p_1 \cdot \Delta}{p_н},$$ (4)

Where $\Delta = \frac{p_н \cdot T_a \cdot R_a}{p_a \cdot T_н \cdot R_н}$ - The ratio of air density,

χ = 1.4 – adiabatic index.

For example, if the maximum pressure drop Δp_1= 10 kPa, and $\Delta \approx 1$ coefficient ε were the accepted minimal value,

$$\varepsilon = 1 - \frac{3}{4 \cdot \chi} \cdot \frac{\Delta p_1 \cdot \Delta}{p_н} = 1 - \frac{3}{4 \cdot 1.4} \cdot \frac{10 \cdot 1}{101.325} = 0.947$$ (5)

Thus, the formula for calculating the flow rate has the following form:

$$Q = 10^{-3} \cdot \varepsilon \cdot \mu \frac{\pi d^2}{4} \sqrt{\frac{2 \cdot 10^3}{0.463 \frac{p_a^1}{273.15 + t^o C}} \Delta p_1}$$, L/s, (6)

Or after the intermediate calculations:

$$Q = 0.0516 \cdot \varepsilon \cdot \mu \cdot d^2 \sqrt{\frac{273.15 + t^o C}{p_a^1} \Delta p_1}, \text{ L/s}, \quad (7)$$

From which we get the formula for calculating the diameter of the nozzle

$$d = \sqrt{\frac{Q}{0.0516 \cdot \varepsilon \cdot \mu \sqrt{\frac{273.15 + t^o C}{p_a^1} \Delta p_1}}}. \quad (8)$$

For practical calculation of nozzle diameter, we take in advance the following parameters:

$\Delta p_1 = p_{1\text{макс}}$ - The maximum operating pressure for pressure sensor (by passport);

ε = 1- To be confirmed by Formula (5);

μ = 0.98- The flow rate coefficient value, within the recommendation range by Ref. [3], and which is to be confirmed at the final trials construction;

p_a^1 = 760 mm рт. Column - pre- setting value by atmospheric pressure, which should be accounted at each flow measurement through the Venturi nozzle;

$t = 20^o C$ - The air temperature in the measuring room, which is also to be accounted for each flow measurement.

The obtained data must be confirmed when carrying standard, including metrological, certification, and must be tested on the installation according to the experiment in Figure 2., which presents a principal pneumatic circuit for devices under studying type(differential pressure-flow characteristics DPF) and devices for creating resistance and calibration of air flow measurement. To create a stable air flow while purging device type DPF, a power source of about 1600 watts is required. Using a calibrated (reference) flow meter allows us to assess the error generated by the flow meter, and if necessary, can carry out corrections of the flow coefficient values in order to minimize the error.

Constructively, DPF apparatus consists of a flow meter PA $_{DPF}$ based on a Venturi nozzle, block pressure sensors BPS, a module analog-digital converter (ADC), and a personal computer (PC) with USB interface. In the unit of flow meter PA $_{DPF}$ performed inside a cylindrical diffuser with the extension diameter directed toward the source of air intake. A flow meter junction was fixed to the unit with a reverse valve (RV) and a Pressure Measuring Point (PMP). Check resistance (or a set of resistances), which indicated flow controller (FC), was mounted to the outlet hole of the junction.

In the BPS block, pressure sensors PS1… PS4 were replaced with electrical terminals and flexible tubes (pipes) for communication pressure sensors with the flow meter PA $_{DPF}$ (PS1) and pressure measurement points C and D in the flow controller FC (T2 and T3). Flexible tube T4 was used for simultaneous testing (checking) of the pressure sensor PS1… PS4. The place for pressure sensors measuring was the interconnection pipelines T1 ... T3:

Where:

- PS1-T1- pressure sensor for flow meter;
- PS2-T2- pressure sensor for measuring in nasopharings;

- PS3-T3- pressure sensor for measuring in vizard;
- PS4-T4- pressure sensor for breasting expiration phase registration.
- Reverse valve (RV) serves to limit the excessive pressure to avoid sensor damage to PS1… PS4. Pressure Measuring Points PMP allows us to connect the additional pressure transducer (if necessary).

The Device DPF Provides

Simultaneous control of the pressure drop and flow rate in the testing channel (tract or flow controller);

Processing obtained test results by constructing graphic dependence of the pressure drop from the flow rate and by calculating the ratio of flow to pressure drop and airflow power.

Determination of the air flow was provided by measuring the pressure at the diffuser inlet, by calculating the formula linking the parameters of pressure drop and flow rate in a turbulent quadratic dependence mode, and by using calibration (reference) flow meter PA_R.

To provide a flow rate measurement in the full range of pressure transducer PS1 (to improve measurement accuracy), the DPF device is completed with flow meters PA_{DPF} with two or three nominal values of nozzle diameters. $PA_{\mathbf{DPF}}$ flow meter can be installed directly on the block BPS or at some distance from the unit, in range length of interconnecting piping T1 ... T3.

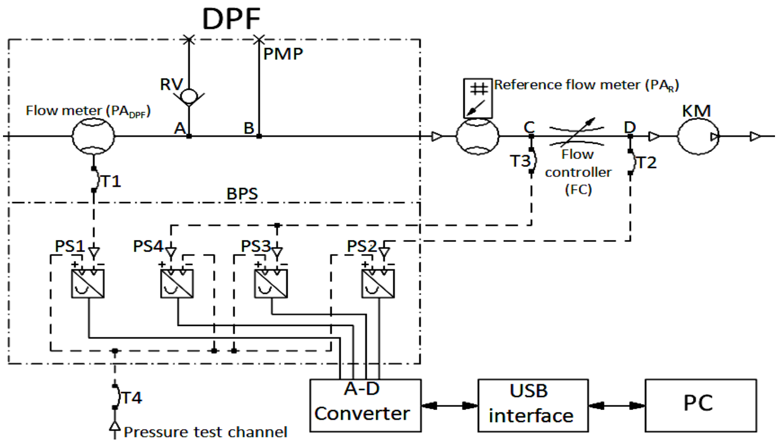

Figure 2: Pneumatic Circuit Diagram Bench Installation for Metrological Certification Devices DPF

To calculate the actual (adjusted) coefficient values, flow rate was obtained from Equation (7) using the following formula:

$$\mu_{\text{ф}} = \frac{19.38 \cdot Q_{\text{э}}}{\varepsilon \cdot d^2 \sqrt{\frac{273.15 + t\,^{\circ}C}{p_{\text{a}}^1} \Delta p_1}} = A \cdot \frac{Q_{\text{э}}}{\sqrt{\Delta p_1}}, \tag{9}$$

Where:

$Q_{\text{э}}$ - Air flow, measured by calibrated flow meter, L / s,

$$A = \frac{19.38}{\varepsilon \cdot d^2 \sqrt{\frac{273.15 + t\,^{\circ}C}{p_{\text{a}}^1}}}$$ -Coefficient, (10)

Each calculation mode of measurement was performed due to possible ambient temperature changes $t^{o}C$ and atmospheric pressure p_{a}^{1}, as well as the existence of functional dependence of correction factor ε (4), taking into account the expansion atmospheric air in the flow meter on pressure drop Δp_1 as well as the relations of air density Δ.

To assess the repeatability of the results and actual correctness, we obtained (specified) values by flow coefficient considering functional dependence:

$$Q = k\sqrt{\Delta p_1} \text{ ,L/s,} \tag{11}$$

Where:

k - Coefficient of proportionality between flow rate and square root of the pressure drop

$$k = 0.0516 \cdot \varepsilon \cdot \mu_F \cdot d^2 \sqrt{\frac{273.15 + t^{o}C}{p_{a}^{1}}}, \tag{12}$$

d and μ_F - diameter of nozzle and flow coefficient, respectively, which were considered constant for the studied flow meter.

The parameters ε; μ; p_{a}^{1} и $t^{\circ}C$ are considered constant for each test mode.

Next, for each test mode, the value of the coefficient k was calculated using the formula

$$k = \frac{Q}{\sqrt{\Delta p_1}}. \tag{13}$$

By deviation values, the stability of testimony flow meter was evaluated in a full range of flow measurement:

$$\delta_k = \frac{k_{MAX} - k_{MIN}}{k_{MAX}} 100 \text{, \%.} \tag{14}$$

As an Example, we Present the Results of Coefficient Calculation k, as Obtained by Testing Full-Scale Models of Flow Meters

- When d = 7 mm k = 3.4% in the range Q = 0.51…4.153 L/s;
- When d = 8 mm k = 4.4% in the range Q = 0.804…6.018 L/s;
- When d = 9 mm k = 0.2% in the range Q = 1.09…7.9 L/s.

The final step in creating the device is considering its state metrological certification, which establishes the relative error of flow rate measurement.

$$\frac{Q - Q_R}{Q_R} 100\% ,\qquad (15)$$

Where

Q - the flow rate of air through verifiable flow meter PA_{DPF} determined by calculating Formula (7), l / s,

Q_R - Air flow, measured calibration (reference) flow meter PA_R, L / s.

CONCLUSIONS

- A method for calculating nozzle diameter was designed to determine pressure drop and flow rate characteristics of human nasal passages.
- Standard studying and metrological verification pointed on the possibility of obtaining sufficiently reliable measurement results when using a flow meter that is based on a Venturi nozzle.
- The prospect of further work is complex studies of the flow meter as part of a device for diagnosing an aerodynamic nasal passages function.

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