Samara State Aerospace University

D.A. Uglanov

Subsonic gas flow in the channel with variable and constant section area

methodology instructions for laboratory works

Samara, 2014

Contents

1. Subsonic gas flow in the channel with variable section area 3

  1.1 Theoretical basis of the experiment 3

  1.2 Laboratory unit description 6

  1.3 Work sequencing 8

  1.4 Data reduction process 10

  1.5 Report contain 11

  1.6 Test questions 12

  1.7 Reference literature 12

2. Subsonic gas flow in the channel with constant section area 13

  2.1 Theoretical basis of the experiment 13

  2.2 Laboratory unit description 15

  2.3 Work sequencing 16

  2.4 Data reduction process 18

  2.5 Report contain 21

  2.6 Test questions 21

  2.7 Reference literature 22

1. Subsonic gas flow in the channel with variable section area

The purposes of the work are the experimental determination of the motion velocity profile in the opposite section of the gas flow and experimental determination of the static pressure, mean velocity and another parameters change along confusor and diffuser axis.

1.1 Theoretical basis of the experiment

Subsonic confusor is the narrowing channel (fig. 1.1,a) and subsonic diffuser is a expansion channel. On fig. 1,b subsonic combined channel, which consists of confusor and diffuser and is called Venturi tube, is presented.

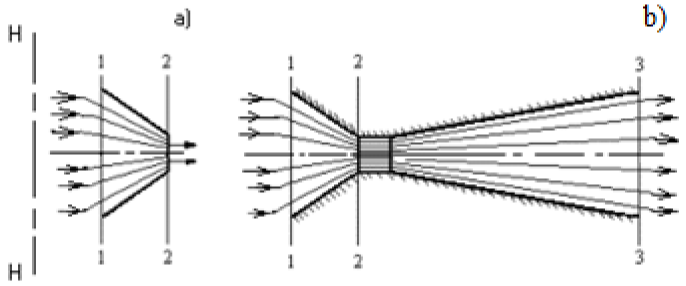

Fig. 1.1. Flow scheme in the subsonic confusor and diffuser

Gas motion in them is carried out due to static pressure difference in the inlet and outlet sections if the gas is fed with increased pressure in the inlet or if there is a rarefaction in the outlet section,

Gas flow research come to determination of its velocity c, pressure p. temperature T, density ρ, stagnation temperature T^* and stagnation pressure p^* during the energy exchange between flow and the environment.

The connection between the parameters of the 1-d steady gas flow in some flow sections 1-1 and 2-2 (fig. 1.1) is expressed trough continuity equation (1.1), energy equation (1.2) and (1.3), expressed trough the enthalpy i, i^*, Bernoulli equation (1.4), entropy equation (1.5) and gas condition equation (1.6) and (1.7).

$$\rho_1 \cdot c_1 S_1 = \rho_2 \cdot c_2 S_2 , \qquad (1.1)$$

$$q_н - l_{мех} = (i_2 - i_1) + \frac{c_{2ср}^2 - c_{1ср}^2}{2} , \qquad (1.2)$$

$$q_н - l_{мех} = (i_2^* - i_1^*) , \qquad (1.3)$$

$$-l_{mech} = \int_{1}^{2} \frac{dp}{\rho} + \frac{c_{2cp}^{2} - c_{1cp}^{2}}{2} + h_{r(1-2)}, \qquad (1.4)$$

$$\left(\frac{T_2}{T_1}\right)^{\frac{k}{k-1}} \cdot \frac{p_1}{p_2} = \left(\frac{T_2^*}{T_1^*}\right)^{\frac{k}{k-1}} \cdot \frac{p_1^*}{p_2^*}, \qquad (1.5)$$

$$\frac{p_2}{\rho_2 T_2} = \frac{p_1}{\rho_1 T_1}, \qquad (1.6)$$

$$\frac{p_2^*}{\rho_2^* T_2^*} = \frac{p_1^*}{\rho_1^* T_1^*}, \qquad (1.7)$$

where S – flow section area;

$q_{н}$ is specific heat transferred from the environment to the length between sections;

l_{mech} is specific mechanical work on the flow in the described area;

$h_{r(1-2)}$ are hydraulic losses of the specific energy which are equal to the specific flow work against the internal friction forces (viscosity) on the described area.

If heat exchange with the environment through the walls can be neglected, gas flow in the confusor and diffuser can be considered as energetically insulated. Then, equations (1.2), (1.3) and (1.4) will take next form:

$$i_1 - i_2 = \frac{c_{2cp}^{2} - c_{1cp}^{2}}{2}, \qquad (1.8)$$

$$i_1^* = i_2^*, \qquad (1.9)$$

$$\frac{k}{k-1}\left(\frac{p_1^*}{\rho_1} - \frac{p_2}{\rho_2}\right) = \frac{c_{2cp}^{2} - c_{1cp}^{2}}{2} + h_{r(1-2)} \qquad (1.10)$$

$$0 = \frac{k}{k-1}\left(\frac{p_1^*}{\rho_{11}^*} - \frac{p_2^*}{\rho_2^*}\right) + h_{r(1-2)} \qquad (1.11)$$

In this case the stagnation temperature T * along the axis of the diffuser and confusor is not changed. As result of the internal friction of the flow, wall friction and hydraulic losses in the entrance of the channel, stagnation pressure p^* will decrease.

Streamline form will be exactly as it shown on the fig. 1.1, consequently, from H-H section to 2-2 opposite section of the flow is decreased.

In subsonic confusor polytrophic gas expansion process takes place which is followed by increasing of the flow velocity along the channel axis and decreasing of the static pressure, temperature and density. In section, normal to confusor channel axis, static pressure is not changing (change is neglected) and stagnation pressure near the channel walls is less than near the axis due to the wall friction losses in the boundary layer. As a result, discharge velocity near the walls is less than near the axis.

On fig. 1.1 2-3 length is a diffuser. In the diffuser polytrophic gas compression process takes place which is followed by decreasing of the flow velocity along the channel axis and increasing of the static pressure, temperature and density. In the opposite section of the diffuser as well as of the confusor static pressure can be considered constant and stagnation pressure near the wall is less than near the axis. Difference is that in the diffuser channel decreasing of the stagnation pressure and velocity in the direction to the wall is more significant than in the confusor.

For every point in the flow connection between the parameters is written through expressions:

$$T^{*} = T + \frac{k-1}{kR} \cdot \frac{c^{2}}{2} \tag{1.12}$$

$$\frac{p}{\rho^{*}} = \left(\frac{T}{T^{*}} \right)^{\frac{k}{k-1}} \tag{1.13}$$

$$\frac{\rho}{\rho^{*}} = \left(\frac{T}{T^{*}} \right)^{\frac{1}{k-1}} = \left(\frac{p}{p^{*}} \right)^{\frac{1}{k}} \tag{1.14}$$

Aforementioned expression can be written through the gas dynamic functions:

$$\tau(\lambda) = \frac{T}{T^{*}} = 1 - \frac{k-1}{k+1}\lambda^{2} \tag{1.15}$$

$$\pi(\lambda) = \frac{p}{p^{*}} = \left(1 - \frac{k-1}{k+1}\lambda^{2} \right)^{\frac{k}{k-1}} \tag{1.16}$$

$$\varepsilon(\lambda) = \frac{\rho}{\rho^*} = \left(1 - \frac{k-1}{k+1}\lambda^2\right)^{\frac{1}{k-1}} \qquad (1.17)$$

$$q(\lambda) = \left(\frac{k+1}{2}\right)^{\frac{1}{k-1}} \cdot \lambda \cdot \left(1 - \frac{k-1}{k+1}\lambda^2\right)^{\frac{1}{k-1}} \qquad (1.18)$$

$$y(\lambda) = \left(\frac{k+1}{2}\right)^{\frac{1}{k-1}} \cdot \lambda . \Big/ \left(1 - \frac{k-1}{k+1}\lambda^2\right) \qquad (1.19)$$

$$\lambda = \frac{c}{a_{кр}} \qquad (1.20)$$

$$a_{кр} = \sqrt{\frac{2k}{k+1} RT^*} \qquad (1.21)$$

Equation (1.1), which expresses gas mass flow rate in the flow through the stagnation parameters and gas dynamic functions, has a next view:

$$G_c = \rho \cdot c \cdot S = m_G \frac{p^* S}{\sqrt{T^*}} q(\lambda) = m_G \frac{pS}{\sqrt{T^*}} y(\lambda), \qquad (1.22)$$

где $m_G = \sqrt{\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}} \cdot \frac{k}{R}}$.

1.2 Laboratory unit description

Unit represents vertical tube 2 (fig.1.2), which have working area on the entrance of tube. Another end of the tube is connected to vacuum pump through feed valve 3 and pipe line 4.

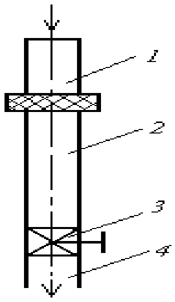

Fig. 1.2. Unit with subsonic confusor-diffuser scheme

Atmosphere air enters working area due to the rarefaction created by vacuum pump. Necessary air flow regimes are set by the feed valve 3. Working area 1 scheme for this laboratory work is presented on fig. 1.3.

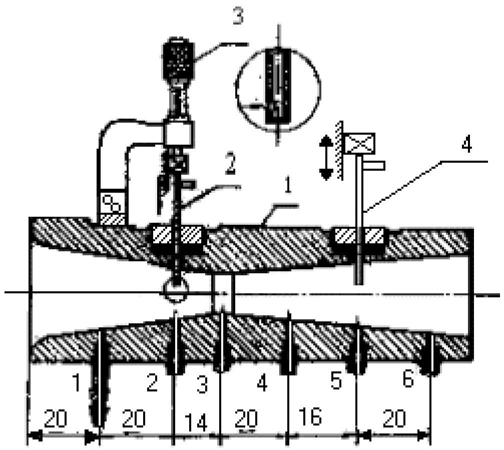

Fig.1.3 Unit working area scheme

№ of sect.	*D*, mm	*S*, mm^2
1	20,8	341
2	14,6	168
3	12	113
4	15,4	187
5	18,6	272
6	22,6	402,5

Air flow through the channel and, at first, its section decrease and, at second, it increases. There are 6 drain orifices along the channel axis in the section 1…6 for static pressure measuring. Stagnation pressure receivers represent tubes with small diameter (d=1 mm) with orifices directed against the flow. These receivers detect flow stagnation pressure in the orifices locations. Receivers displacement along the channel section radius is accomplished by micrometer screws 3. Two rounds of the micrometer screw correspond to 1 mm of stagnation pressure displacement along the radius. Pressure measurement is carried out by standard vacuum pump of spring type.

1.3 Work sequencing

1. The protocol for devices measurement recording and calculation results is prepared.

2. Air temperature $t_н$ and pressure $p_н$ in the classroom are measured.

3. Vacuum pump is turned on.

Example of the experiment protocol.

Measured values						
№ of sec	x, mm	D, mm	p_{vac}, div.	№ of point in 5th section	r$_5$, mm	$p^*_{5\,вак}$, div.
1						
2						
3						
4						
5						
6						

Results of the calculation													
№ of sec	p, kPa	p^*_{mean}, kPa	$\pi(\lambda)$	λ	c_{cp}, m/sec	$\tau(\lambda)$	T, K	№ of point in 5th section	p_5, kPa	p^*_5, kPa	$\pi(\lambda)$	λ_5	c_5, m/sec
1													
2													
3													
4													
5													
6													

4. Subsonic flow regime is set by gradually opening of the feed valve (fig. 2). Maximal air flow velocity is in the narrow section of the confusor (section 3,

fig. 3). Because of that to maintain the subsonic flow regime along the entire channel it is necessary to observe the condition that static pressure in the section 3 is bigger than static pressure in the critical section, i.e. $p_3 > p_{кр} = 0{,}528 p_н$.

5. Static pressure p_{vac} of the air is measured along the flow in six sections. During these measurements stagnation pressure receivers must be excluded from the flow.

6. Stagnation pressure $p^*_{5вак}$ in several points of the air flow along the section 5 radius is measured. By rotation of the micrometer, screw tube is set so that its feed orifice is placed near the wall (point 7, r_1 = 8,8 mm in table 2, fig.1.4).Vacuum pump measurements are recorded. Then, by rotation of the micrometer screw, tube feed orifice is set in the points № 6, 5, 4, 3, 2, 1 and vacuum pump measurements are recorded.

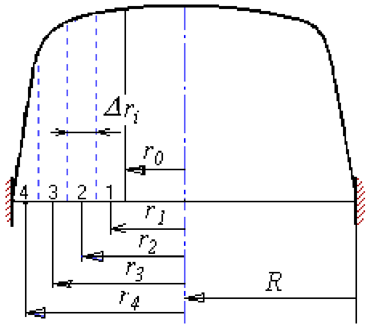

Fig. 1.4 – Mean stagnation pressure profile vs mass flow rate

№ point	confusor		diffuser	
	r_i	Δr_i	Δr_i	Δr_i
1	3,8	1.0	2,8	1,0
2	4,8	1.0	3,8	1,0
3	5,8	1.0	4,8	1,0
4	6,8	1.0	5,8	1,0
5	-	-	6,8	1,0
6	-	-	7,8	1,0
7	-	-	8,8	1,0
	-	-	-	-
r_0	3,3	-	2,3	-
R	7,3	-	9,3	

7. By rotation of the micrometer, stagnation pressure rube is excluded from the flow in section 5 of diffuser.

8. Vacuum pump is turned off and feed valve 3 is shut down (fig. 1.2).

9. The results of the measurements are recorded into the protocol.

1.4 Data reduction process

1. Static pressure p (kPa) is determined by the results of the measurements in 6 sections of the air flow along the confusor and diffuser

$$p = p_н - p_{vac} = p_н - p_{vac,\ div}\, n,$$

where n is division value (kPa) of the standard gauge.

2. Stagnation pressure p (kPa) is determined by the results of the measurements in 6 sections of the air flow along the confusor and diffuser

$$p^*_5 = p_н - p^*_{vac5} = p_н - p^*_{5vac,\ div}\, n,$$

where n is division value (kPa) of the standard gauge.

3. Gas dynamic function value $\pi(\lambda) = p_5 / p^*_5$ is determined in the points of flow along the section 5 radius of the diffuser. It is assumed that static pressure doesn’t change in the section.

4. Relative velocity λ_5 is determined from the expression (1.16) or table of gas dynamic function for every point of diffuser section 5 radius.

5. Air critical velocity is determined by the expression (1.21). Stagnation temperature T^* is equal to atmosphere temperature $T_н$ on the entrance of the unit.

6. Air velocity in the points along diffuser section 5 radius is determined from the expression (1.20).

7. Mean stagnation temperature p^*_{5mean} in section 5 of diffuser is determined by the expression

$$p^*_{5mean} = \frac{\left(p^*_5\right)_{r0} \cdot \pi \cdot r_0^2 + \sum_{i=1}^{i=7} p^*_{5i} \cdot 2\pi \cdot r_i \Delta r_i}{\pi \cdot R^2},$$

where $(p^*_{5cp})_{r0}$ is constant stagnation pressure in the flow core with radius $r_0 = 2{,}3$ mm.

p^*_5 is a stagnation pressure in section 5 on the current radius in points 1-7;

Δr is radius increment which is equal to distance between neighboring points of p^*_5 measurement; $\Delta r = 1$ mm = *const*;

R is diffuser section 5 radius, $R = 9{,}3$ mm.

8. Mean stagnation pressure p^*_{mean} for the rest sections along the channel length is determined. For this purpose it is necessary to plot a p^*_{mean} change curve from two values of p^*_{mean} in sections 5 and 0. In the entrance of channel $(p^*_{mean}) = p_{н}$. p^*_{mean} values for every section of flow is determined from the curve.

9. Gas dynamic function values $\pi(\lambda) = \frac{p}{p^*_{cp}}$ in 6 sections of the air flow along the confusor and diffuser.

10. The relative velocity λ is determined from the expression (1.16) or tables of gas dynamic function values in 6 sections of flow.

11. Mean air motion velocity c_{mean} is determined from the expression (1.20) in 6 sections of the flow along confusor and diffuser.

12. Gas dynamic function $\tau(\lambda)$ values are determined by expression (1.15) or tables of gas dynamic function values for air.

13. Static temperature T of the air is determined from the $T = \tau(\lambda) \cdot T^*$ in 6 sections of flow. Stagnation temperature is the same along the flow and is equal to atmosphere air temperature $T_{н}$.

14. Air mass flow rate G in section 1 is determined by expression (1.22). Flow section area in section 1 is equal to $S_1 = 341 \cdot 10^{-6}$, m^2.

15. The results of the calculation are recorded in the table for results of the calculation.

1.5 Report content

1. Experiment protocol with unit working area scheme.

2. Plots of the static pressure p and mean stagnation pressure p^*_{mean} change along the confusor and diffuser length (sections 1-6).

3. Plot of the mass mean velocity of the air motion c_{mean} change along the length of the confusor and diffuser (sections 1-6).

4. Plot of the static temperature T and stagnation temperature T^* change along the confusor and diffuser length.

5. Plots of velocity c_5 and stagnation pressure p^*_5 change along the section 5 radius of the air flow.

6. Conclusions.

1.6 Test questions

1. Why does the air flow in channel can be considered as energetically insulated?

2. Which forces cause flow acceleration in the confusor part of the channel and deceleration in the diffuser part of the channel?

3. Which energy conversation occur in the energetically insulated confusor and diffuser channels?

4. Why does experiment should be carried out with condition that pressure in the narrow section is bigger than 0.55…0.60 of atmosphere pressure?

5. How does the coordinates of points for stagnation pressure receivers application are determined?

6. Why do the air stagnation pressure and temperature in the entrance of the channel are nearly the same as pressure and temperature of atmosphere?

7. Why does stagnation temperature of the flow is constant along the channel and stagnation pressure gradually decrease along the channel as well as from the flow core to the walls?

8. What is stagnation pressure near the walls?

9. What condition required for stagnation pressure be the same for entire flow?

10. Why does this laboratory work require vacuum and vacuum pumps?

1.7 Reference literature

1. Abramovich G.N. Applied gas dynamics. Nauka. 1991.

2. Sergel O. S. Applied hydrogasdynamic. Nauka. 1981.

2. Subsonic gas flow in the channel with constant section area

The purpose of the work is experimental research of friction and heat influence on the subsonic air flow moving in the cylinder tube of constant section and determination of the friction coefficient in case of air motion without heating.

2.1 Theoretical basis of the experiment

Let's consider friction influence on the change of subsonic flow parameters in the cylinder tube. Heat exchange with environment can be neglected, i.e. $q_{н} = 0$. Some pressure difference (p_1–p_2) on the entrance and exit of the tube (fig. 2.1) is used for creation of the steady flow.

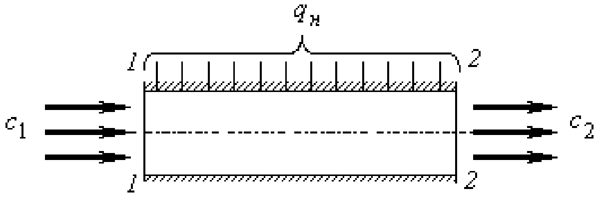

Fig. 2.1 Flow scheme in the tube

From the Bernoulli equation

$$\frac{dp}{\rho} + \frac{d(c^2)}{2} + dh_{fr} = 0 \tag{1}$$

it is followed that pressure difference is required for the flow acceleration and overcoming friction losses. It is obvious, that with the same pressure difference flow acceleration (and correspondingly velocity c_2 on the exit of the tube) will be more if friction is absent, i.e. if gas is ideal. However, it can be proved, that subsonic flow in the tube with constant section area with friction presence cannot be accelerated to velocity, higher than critical velocity, no matter how high the pressure difference is. With small enough pressure difference (p_1–p_2), if it is equal to difference Δp_{fr}, which is spend on friction overcoming, flow will move in tube without acceleration, i.e. with constant velocity. From the heat equation:

$$dq_{н} = di + \frac{d(c^2)}{2} \tag{2.2}$$

it is clear, in the tube without heat exchange with environment ($q_н = 0$) the flow, moving with acceleration ($dc > 0$) is refrigerated ($di < 0$).

Thus, despite the presence of friction which connected with heat adding, static temperature T_2 of the flow moving with acceleration on the exit of the tube is less than initial T_1 temperature. It is connected with flow heat spending on its acceleration. In particular case of viscous gas motion with constant velocity in the tube with constant velocity, the static temperature of the flow is constant. From the equation (2.2) it is followed, that in case of $dq_н=0$ gas stagnation temperature doesn't change, i.e. . $T_1^*=T_2^*$. However, from the equation (1.1) it is clear that with friction presence ($dh_{mp} > 0$) stagnation pressure in the tube without heat exchange inevitably decreases, i.e. $p_2^*<p_1^*$. Elementary friction work can be expressed as a part of flow kinetic energy

$$dh_{mp} = \xi \frac{c^2}{2} \cdot \frac{dl}{d} \tag{2.3}$$

where ξ is friction coefficient, d – tube diameter, dl – elementary tube area length. Continuity equation for compressible fluid motion in the tube in differential form has a next view:

$$d(\rho \cdot c \cdot S) = 0 \tag{2.4}$$

From (2.4) it is followed, that in the tube with constant section area ($S = const$) flow acceleration is connected with decrease of the gas density. Joint solving of (2.1), (2.2), (2.3), (2.4), for the case of $dq_н = 0$ after the integration we get

$$\frac{1}{\lambda_1^2} - \frac{1}{\lambda_2^2} - \ln\frac{\lambda_2^2}{\lambda_1^2} = \frac{2k}{k+1}\xi\frac{l}{d} \tag{2.5}$$

Expression (2.5) can be used for friction coefficient ξ determination. It should be taken into account, that in presented above equations, flow c, T, ρ, p parameters are mean parameters in the tube section. Indeed, gas parameters in tube section are changing, especially gas velocity c, which varies from 0 near the wall to c_{max} on the tube axis. Substitution of the variable parameters by mean constant significantly simplifies task solving, but physical entity of the phenomena is not fully revealed.

The second part of the work is experimental research of heating influence on viscous gas flowing in cylindrical tube. Influence of the exact heat adding is determined by comparison of the gas parameters and flow characteristics in case of heating and friction (flow of the real gas with only heating cannot be realized) with the case of flow with only friction.

The tube with constant diameter, in which flow accelerated with heating, is called heat nozzle. From the theory of its nozzle it is known that with presence of the pressure difference ($p_1 - p_2$) subsonic flow with heating ($dq_{н} > 0$) is accelerated and gas density decreases. Heating causes static temperature T and stagnation temperature T^* increasing along the tube length in the flow direction. Stagnation pressure p^* decreases due to the irreversible process of heat energy transfer to kinetic energy. Stagnation pressure decreasing in the heat nozzle is called heat resistance. Gas temperature increasing with heating causes bigger density decreasing (ρ is inversely proportional to temperature) than decreasing due to the velocity increasing (c is proportional to square root of temperature). As result gas flow rate through the tube with heating is decreased as it can be seen from continuity equation (2.4). So, gas heating in the tube with presence of pressure difference ($p_1–p_2$) causes velocity increasing c and density ρ and stagnation pressure p^* decreasing similar to flow with friction.

2.2 Laboratory unit description

Unit working area for this laboratory work represents (fig. 2.2) vertical cylindrical tube with inner diameter d=9 mm and length l=930 mm, connected t the pipe line of common vacuum system through the feed valve. Atmosphere air from the classroom through inlet junction pipe 1 is sucked through the tube under vacuum pump action. The pressure difference changing in the tube (change of working regimes) is accomplished by feed valve in the pipe line or throttle 7 in tube (fig. 2.2). Air heating is provided by electric spiral 5, which is reeled in tube and lock by shell 3 with asbestos heat insulation 4. For measurement of the air static pressure, there are orifices with tubes 2, placed starting on section 1 on equal distances l=100 mm between each other, connected with vacuum gauges. For stagnation pressure measurement on the exit of the tube (section 10), receiver 8 with traversing gear is installed which allows to move receiver along the tube exit section area radius. For flow stagnation temperature measurement on the exit of the tube, chromel-copel thermocouple, which connected to potentiometer or millivoltmeter is used.

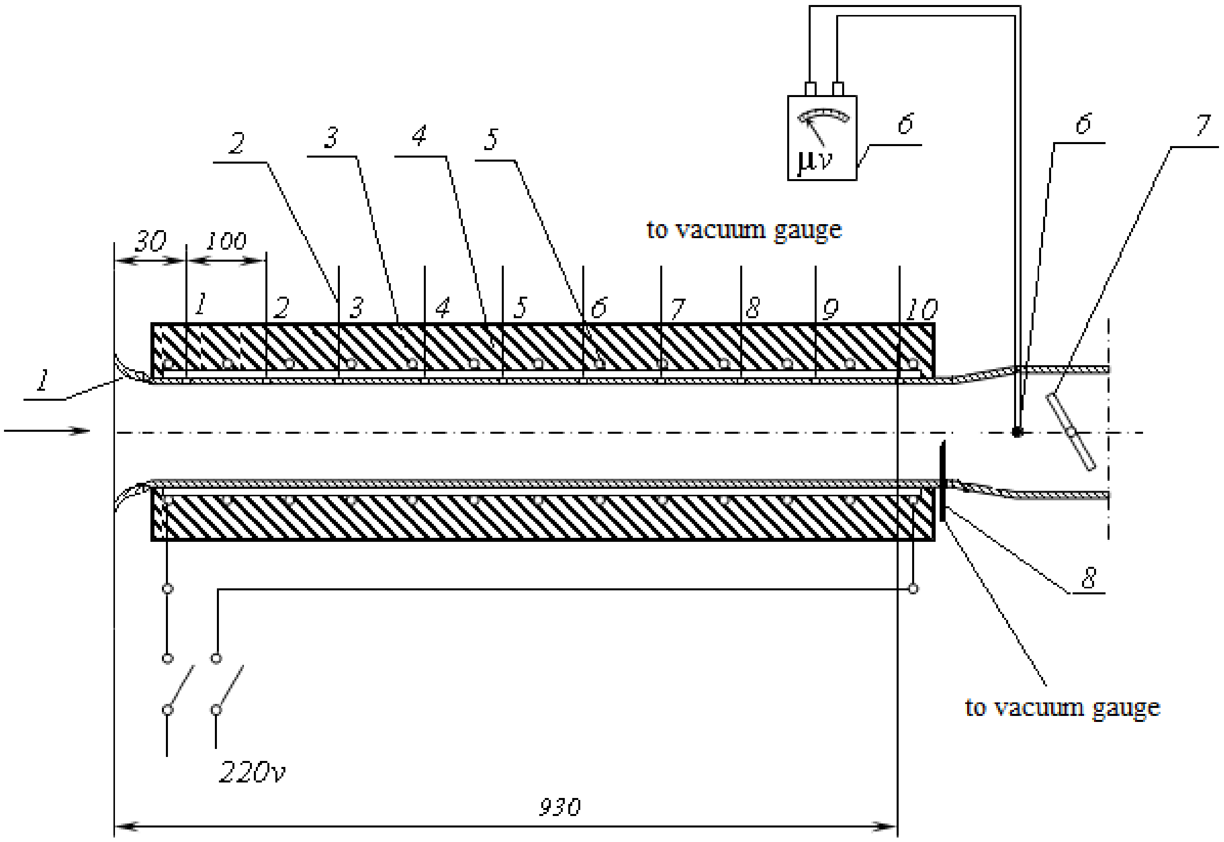

Fig. 1.1 – Unit working area scheme

2.3 Work sequencing

1. The protocol for devices measurement recording and calculation results is prepared.

2. Air temperature $t_н$ and pressure $p_н$ in the classroom are measured.

3. Vacuum pump is turned on.

4. Unit feed valve is gradually opened. On the tube working area throttle 7 must be opened.

5. The measurements of the vacuum gauges, which are connected with statc pressure receivers in the flow sections along the tube, are recorded.

6. Stagnation pressure in the tube exit section is measured along the radius in three points: near the wall, on the middle of the radius and on the tube axis. For that purpose it is necessary to move stagnation pressure receiver by traversing gear screw rotation.

Experimental protocol example

Measured values										
Regime without heating										
№ sect.	1	2	3	4	5	6	7	8	9	10
p_{vac}, div										
p^*_{vac}, div										
Regime with heating										
p_{vac}, div										
p^*_{vac}, div										
E_{meas}, mV										
Calculated values										
Regime without heating										
№ sect.	1	2	3	4	5	6	7	8	9	10
l, mm	30	130	230	330	430	530	630	730	830	930
p, kPa										
p^*_{mean}, kPa										
T^*, K										
c_{mean}, m/sec										
c_{cr}, m/sec										
T, K										
ρ, kg/m^3										
G, kg/sec										
Regime with heating										
№ sect.	1	2	3	4	5	6	7	8	9	10
l, mm	30	130	230	330	430	530	630	730	830	930
p, kPa										
p^*_{mean}, kPa										
T^*, K										
c_{mean}, m/sec										
c_{cr}, m/sec										
T, K										
ρ, kg/m^3										
G, kg/sec										

7. Electric spiral is turned on without changing air flow regime (feed valve and throttle location) and heat is carried out during 7-10 min. It should be observed that heating doesn’t exceed 3,7 mV on the millivoltmeter (potentiometer) scale, which corresponds to air temperature $t = 120^0$ C. It is necessary to avoid the tubes 2 unbrazing (fig. 2.2).

8. Paragraphs 5,6 are repeated until air flow with heating regime is reached.

9. Air stagnation temperature on the tube exit is recorded by potentiometer measurements E_{meas}, mV.

10. Electric spiral is turned off and after 3-5 min vacuum pump is also turned off.

11. The results of all measurements are recorded in protocol.

2.4 Data reduction process

1. By results of the measurements, absolute static pressure p in sections of the air flow along the tube axis is determined

$$p = p_{\text{н}} - p_{vac} = p_{\text{н}} - p_{vac,div} \cdot n,$$

where $p_{\text{н}}$ is air atmosphere pressure, kPa;

n is a division value of the standard vacuum gauge.

2. By results of the measurements, absolute stagnation pressure p^* in exit section of the tube in three points along the radius: near the wall, on the midpoint of radius and tube axis

$$p^* = p_{\text{н}} - p^*_{vac} = p_{\text{н}} - p^*_{vac,div} \cdot n,$$

where $p_{\text{н}}$ is air atmosphere pressure, kPa;

n is a division value of the standard vacuum gauge.

3. Mean stagnation pressure p^*_{mean} in the exit section of the tube is determined as a arithmetic mean of three aforementioned points values

$$p^*_{mean} = \frac{\sum\limits_{i=1}^{n=3} p_i^*}{3}.$$

4. Mean stagnation pressure p^*_{cp} in sections 1-9 is determined with condition that it changes linear from the entrance section 0 (where it is equal to $p_н$) to exit section 9 (where it is equal to p^*_{mean}).

5. Paragraphs 1,2,3,4 are repeated for regimes with and without heating.

6. Stagnation temperature T^* is determined in the exit section of the tube on the regime with heating

$$T^* = t + 273,$$

where t – heated air temperature in Celsius, measured by the thermocouple.

t value is determined by standard reference table for chromel-copel thermocouple (look at addendum). Reference table is composed with condition that cold junction has temperature 0^0 C. During the experiment in laboratory work, cold junction has a temperature of the environment. Thus, to use reference table it is necessary to insert an amendment. Then, thermal emf, corresponding to value of the reference table, is equal to:

$$E_{tab} = E_{meas} + E_{c.j.},$$

where E_{meas} is thermal emf, corresponding to potentiometer measurement during the experiment,

$E_{c.j.}$ is thermal emf, determined by reference table for the chromel-copel thermocouple by measured atmosphere air temperature $t_н$ in the classroom.

7. Stagnation temperature in sections 1-9 on heating regime is determined with condition of linear dependency of its changing from the environment temperature $T_н = t_н + 273$ in the entrance section 0 to T^* in air flow section on the tube exit.

On regimes without heating stagnation temperature T^* in all sections remains constant and equal to $T_н$.

8. Air velocity c_{mean} in all section along the tube axis is determined

$$c_{mean} = \sqrt{\frac{2\kappa}{\kappa - 1} R T^* \left[1 - \left(\frac{p}{p^*_{mean}} \right)^{\frac{\kappa - 1}{\kappa}} \right]}$$

where for air k=1,4, R=287 J/kg·K.

9. Critical air velocity in all sections along the tube axis is determined

$$c_{cr} = a_{cr} = \sqrt{\frac{2\kappa}{\kappa+1}RT^{*}}.$$

10. Static air temperature T in all sections along the tube axis is determined

$$T = T^{*} - \frac{\kappa-1}{\kappa R}\cdot\frac{c_{mean}^{2}}{2}.$$

11. Air density ρ in all sections along the tube axis is determined

$$\rho = \frac{p}{RT}.$$

12. Air mass flow rate G_c in all sections of the flow is determined

$$G_c=\rho c_{cp}\cdot S,$$

where S – is air flow section area.

$$S = \frac{\pi}{4}d^{2} = 63{,}6\cdot 10^{-6}, \text{м}^{2}.$$

13. Coefficient of air stagnation pressure changing in the tube is calculated

$$\sigma = \frac{p_{10}^{*}}{p_{1}^{*}}.$$

14. Calculations in paragraphs 8-13 are repeated for regimes with and without air heating.

15. Coefficient of linear hydraulic losses for friction ξ in tube for regime without heating is calculated from the expression

$$\frac{1}{\lambda_{н}^{2}} - \frac{1}{\lambda_{к}^{2}} - \ln\frac{\lambda_{к}^{2}}{\lambda_{н}^{2}} = \frac{2\kappa}{\kappa+1}\xi\frac{l}{d}$$

where l – is tube length between the entrance and exit sections (sections №1 and 10),

d – tube inner diameter,

λ is relative air velocity in flow sections

$$\lambda = \frac{c_{cp}}{a_{кр}}, \lambda_{н}=\lambda_{1}; \lambda_{к}=\lambda_{10}.$$

16. The results of the calculation are recorded to the protocol table and curves of p, p^*_{mean}, T, T^*, c_{mean}, c_{cr} change along the tube length l are plotted for aur regimes with and without heating.

2.5 Report content

1. Experiment protocol with unit working area scheme.
2. Air static pressure p and mean stagnation pressure p^*_{cp} curves along the tube length l for regimes with and without air heating.
3. Air static temperature p and stagnation temperature p^*_{cp} curves along the tube length l for regimes with and without air heating.
4. Air velocity c_{mean} and critical velocity c_{cr} curves along the tube length l for regimes with and without air heating.
5. Comparison of the experimental results for regimes with and without heating.
6. Conclusions.

2.6 Test questions

1. Why does air flow can be considered as energetically insulated on the regime without heating?
2. Which forces cause flow acceleration in the constant section channel with and without heating?
3. Which energy conversation occur in the flow on each regime?
4. Why does the flow in the entrance channel section can be only subsonic in the conditions given in this laboratory work?
5. How would flow parameters change in the channel of constant section with and without heating if gas is considered as non-viscous?
6. What causes the stagnation pressure losses with and without heating?
7. How to determine stagnation pressure losses caused by inner friction (viscosity) for flow with heating?

8. Why does the air flow rate on the regime with heating is less than on the regime without heating, if negative pressure remains the same?

9. Why do stagnation pressure losses on the regime with heating are bigger than on the regime without heating, if the air flow rate is the same?

10. Compare the gas pressure on the channel exit with critical pressure and negative pressure.

2.7 Reference literature

1. Abramovich G.N. Applied gas dynamics. Nauka. 1991.
2. Sergel O. S. Applied hydrogasdynamic. Nauka. 1981.
3. Lojcjanskij L.G. Fluid mechanics. Nauka. 1987.