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NATIONAL TECHNICAL UNIVERSITY
«KHARKIV POLYTECHNIC INSTITUTE»

METHODOLOGICAL INSTRUCTIONS

to the laboratory work
«Analysis of the Process of Forced Heat Convection
in the Tube Bundle»
of discipline «Theoretical Fundamentals of Heat Engineering»

for students of specialty
141 «Electric Power Engineering,
Electrical Engineering and Electromechanics»

Kharkiv 2021

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Approved
by drafting and publishing
board of university,
transactions № 2 of 29.06.21.

Kharkiv
NTU «KhPI»
2021

Methodological instructions to the laboratory work «Analysis of the Process of Forced Heat Convection in the Tube Bundle» of discipline «Theoretical Fundamentals of Heat Engineering» for students of specialty 141 – «Electric Power Engineering, Electrical Engineering and Electromechanics» / compiler V.V. Pylyov. – Kharkiv: NTU «KhPI», 2021. – 13 p.

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PREFACE

Acquiring an ability to solve problems regarding forced convection is an important part of studying the discipline «Theoretical Fundamentals of Heat Engineering», as far it is the most abundant mode of heat transfer in all kinds of enginery, power plants, heat exchangers, heat-using devices and facilities. An accepted method of solving of such problems in simplified and generalized form provides for usage of similarity theory.

Examination of the process of heat emission of a cylindrical tube in an air flow, and more complicated case of heat emission of a tube bundle, are convenient way to improve knowledge of criterial equation usage and gaining skills of their composing on a base of experimental data.

Hence, the goal of the laboratory work is upgrading knowledge of forced convection, becoming familiar with methods of related experimental investigation and criterial equation set-up.

1. PROBLEM STATEMENT

Formula manipulation over the system of differential equations of convective heat exchange and edge conditions of transverse stationary flow of a medium through a tube bundle results in the criterial equation

$$\mathrm{Nu} = f(\mathrm{Re}, \mathrm{Pr}), \tag{1}$$

where Nu – is Nusselt number

Re – is Reynolds number;

Pr – is Prandtl number.

The flow in bundles usually becomes turbulent very quickly, so occurrence of natural convection with its influence on heat transfer can be ignored. Therefore Grashof number was not included in the equation.

In the particular case the similarity criteria are suitable to be composed in the following way:

$$\mathrm{Nu} = \frac{\alpha d}{\lambda}, \tag{2}$$

$$\mathrm{Re} = \frac{wd}{\nu}, \tag{3}$$

$$\mathrm{Pr} = \frac{\nu}{a}, \tag{4}$$

where α – is circumferentially mean heat transfer coefficient, $W/(m^2 \cdot K)$;

d – is diameter of tubes in the bundle as determining length – the linear dimension that has the most influence on the process course, m;

λ – is thermal conductivity of the medium, W/(m·K);

w – is flow velocity at the bundle minimum cross-section, m/s;

ν – is kinematic viscosity of the medium, m^2/s;

a – is thermal diffusivity of the medium, m^2/s.

All parameters of the medium are taken at the temperature t_∞ of undisturbed flow before the bundle.

In view of air being the flowing medium in the laboratory work, the evident dependence of Prandtl number is traced only on its temperature. With regard to complications of reliable and accurate variation of the temperature of the air inflowing laboratory installation, Prandtl number is regarded as a constant in the work, and Nusselt number in (1) is dependant only on Reynolds one.

Most of criterial equations of heat transfer, including forced convection, have a form of power function, coefficients of which are adjusted to fit the experimental data the best. Then the equation (1) takes the shape

$$\mathrm{Nu} = C\,\mathrm{Re}^{n}\,, \tag{5}$$

where C and n – are constant coefficients.

The intensity of heat transfer increases along the depth of the tube bundle due to additional turbulization in the rows of its tubes. Its influence on the equation (5) can be represented by assigning a distinct value C_i to the multiplier constant for every one of the rows, so that for an *i*-th row it going to take the form

$$\mathrm{Nu}_i = C_i\,\mathrm{Re}^{n}\,. \tag{6}$$

Then the mean heat transfer coefficient for the part of the bundle that includes an *i*-th row and the ones located before it has to fulfill the equation

$$\mathrm{Nu} = C\,\mathrm{Re}^{n} E_i\,, \tag{7}$$

where E_i – correction coefficient dependent on the number of rows.

The task that has to be solved in the work is ascertaining these coefficients and setting-up a criterial equation in the form (5) for one row of tubes or in the form (7) for a part of the bundle as an instructor decides.

2. LABORATORY INSTALLATION DESCRIPTION

A diagram of the experimental installation that is used in the laboratory work is shown in Fig. 1.

The subject tube bundle 1 is installed inside a test section of the foursquare wind tunnel 2 with length of a side *a* = 200 mm.

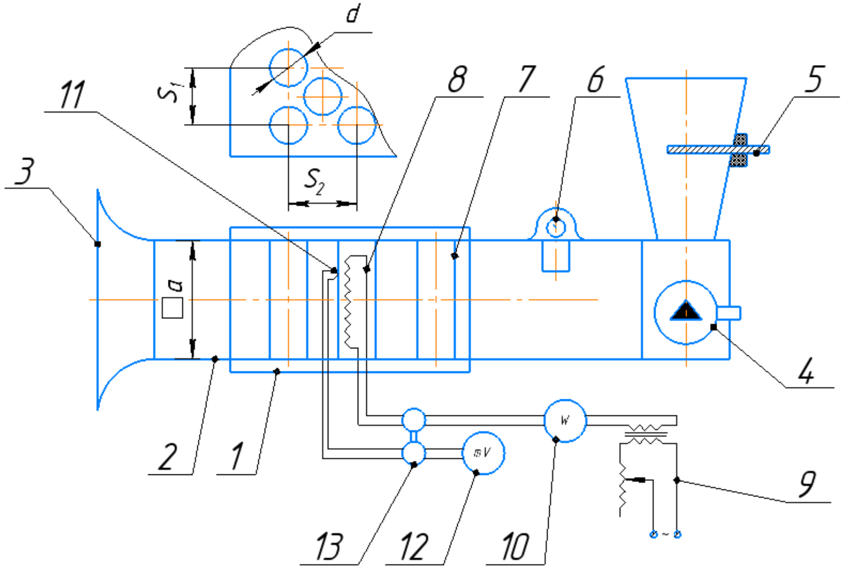

Figure 1 – Experimental installation schematic diagram

The wind tunnel inlet 3 has lemniscate form, it allows the flow of air enter the tunnel without boundary-layer separation and so prevents air heating via the viscous losses of flow energy. For the same purpose the fan 4 that draughts air into the tunnel and the damper 5 that creates hydrodynamic resistance, allowing adjusting the flow velocity, are set in the flow path after the tunnel. This way the undisturbed air flow temperature t_∞ in the bundle may be assumed to be equal the temperature of surroundings t_0. The flow velocity w_0 in the tunnel is measured with a propeller anemometer 6.

There are m = 6 rows of tubes in the bundle with u = 5 tubes in each. The tube bundle has staggered grid pattern, with center-to-center pitch in frontal and depth directions S_1 = 40 mm and S_2 = 30 mm respectively; its thin-walled tubes 7, which have diameter d = 19 mm, are made from brass. The tube material having high thermal conductivity, the local temperatures of the tube surface are very close to each other and cannot be studied reliably, but the mean temperature value becomes possible to estimate by only one measurement.

In the inner part of the middle tube of each row an electrical heater 8 is installed. Its input power *P* can be changed by an adjustable voltage transformer 9 and measured by a wattmeter 10.

The temperature t_w of each heated tube surface is measured by the chromel-kopel thermocouple, the electromotive power (emf) of which $E(t_w, t_0)$ is evaluated by the millivoltmeter 12. To prevent mutual heat influence of the tubes only one tube at a time can be heated, there is a selector switch 13 that simultaneously commutes the doublemake contact of the power line and millivoltmeter circuit to the plug-ins of a definite row.

3. TEST PROCEDURE

Warning: the experimental installation is allowed to be turned on only by the instructor!

Measurements are performed for several operating modes of the installation for each row in accordance with directives of the instructor, beginning from the one most distant from the tunnel inlet. The mode is specified by the pair of chosen positions of the flow damper and voltage transformer.

Before each measurement, the temperature of the tube has to have time to set, which takes 15-20 minutes. The constant tube temperature during 1-2 min can be used as an indication of that the operating mode is set. To reduce this time, the modes have to be ordered on the basis of the expected tube temperature growth: the first mode studying should be followed with increasing the power of the voltage transformer, and reducing the air consumption next.

To find the flow velocity using an anemometer, the number of graduation marks of the anemometer scale that the device arrow passes per 1 s is counted. To transform the result into velocity measurement units a diagram of the anemometer curve is used typically. However, for the specific device used in the work, this curve is a line clearly located at 45° to the axes, and the mentioned values are going to be equal to each other.

To increase the accuracy of the method, measuring the time τ that k turns of the arrow take is recommended instead, and then, to obtain the velocity of the flow within the tunnel, the formula is applied

$$w_0 = \frac{rk}{\tau}, \tag{8}$$

where r = 100 is number of graduation marks on the anemometer scale, and number of turns k is not less than 5.

The velocity of the air flow in the spot of studied heat transfer occurrence in the narrowest section of the bundle can be found from the equation of continuity

$$w = w_0 \frac{F_t}{F_b}, \tag{9}$$

where $F_t = a^2$ is the flow area in the tunnel;

$F_b = F_t - uda$ is the flow area of the partially shadowed bundle section.

The surface temperature t_w of the tube is supposed to be found from the Table 1, which contains the data of the adjusted emf of the thermocouple $E(t_w, 0)$ dependence on the temperature.

Previously, the emf of the cold junction $E(t_0, 0)$ corresponding the ambient temperature must be taken from the same table, and, using reading of the millivoltmeter $E(t_w, t_0)$, the adjusted value calculated

$$E(t_w, 0) = E(t_w, t_0) + E(t_0, 0). \tag{10}$$

The measurement results and the values found on their basis are summarized in Table 2.

Table 1 – Dependence of emf of chromel-kopel thermocouple on the temperature of its hot junction if the temperature of the cold one is 0°C

ºC	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0	0	0.07	0.13	0.20	0.26	0.33	0.39	0.46	0.52	0.59
10	0.65	0.72	0.78	0.85	0.91	0.98	1.05	1.11	1.18	1.24
20	1.31	1.38	1.44	1.51	1.57	1.64	1.71	1.77	1.84	1.90
30	1.97	2.04	2.11	2.17	2.24	2.31	2.38	2.45	2.51	2.58
40	2.65	2.72	2.79	2.86	2.93	3.00	3.06	3.13	3.20	3.27
50	3.34	3.41	3.48	3.55	3.62	3.69	3.75	3.85	3.89	3.96
60	4.03	4.10	4.17	4.24	4.31	4.38	4.45	4.52	4.59	4.66
70	4.73	4.80	4.87	4.95	5.02	5.09	5.16	5.23	5.31	5.38
80	5.45	5.52	5.59	5.67	5.74	5.81	5.88	5.95	6.03	6.10
90	6.17	6.24	6.32	6.39	6.46	6.54	6.61	6.68	6.75	6.83
100	6.90	6.97	7.05	7.12	7.20	7.27	7.34	7.42	7.49	7.57

Table 2 – The table blank for results of the measurement

	t_0 = °C				$E(t_0, 0)$ = mV			
#	$E(t_w, t_0)$, mV	k	τ, s	P, W	$E(t_w, 0)$, mV	t_w, °C	w_0, m/s	w, m/s

4. PROCESSING THE DATA

To obtain the constants in the criterial equations the pairs of Nusselt and Reynolds numbers have to be found for every of the studied installation operating modes using formulas (2) and (3).

The heat transfer coefficients in (2) can be obtained according to Newton's law of cooling

$$\alpha = \frac{Q_c}{(t_w - t_0)F}\,, \qquad (11)$$

where $F = \pi da$ is the tube surface area;

Q_c is the convection component of heat flux from the tube to the air, W.

The total heat flux transferred to the air is equal to the power of the heater in the tube if heat losses from well heat insulated ends of the tube neglected. Considering that heat is transferred to the surroundings by convection and radiation, the convective heat flux can be found as

$$Q_c = P - Q_r, \tag{12}$$

where Q_r is the radiant heat flux, W. Taking into account that all the surfaces in the ambient space should have the temperature of surroundings t_w, it equals

$$Q_r = C_0 \varepsilon \left[\left(\frac{T_w}{100} \right)^4 - \left(\frac{T_0}{100} \right)^4 \right] F, \tag{13}$$

where $C_0 = 5{,}67\, W/\left(m^2 K^4\right)$ is Stefan-Boltzmann constant;

$\varepsilon = 0{,}6$ is emissivity of a polished brass oxide surface;

T_w, T_0 are thermodynamic temperatures of the tube surface and the air, K.

The thermalphysic properties of air in (2), (3) depending on its temperature are presented in Table 3.

Table 3 – Dependence of air properties on the temperature

t_w, °C	16	18	20	22	24
λ, W/(m·K)·10^{-2}	2.558	2.574	2.590	2.606	2.622
ν, m^2/s·10^{-6}	14.70	14.88	15.06	15.24	15.42

To obtain the exponent *n* in the criterial equation, it is convenient to use the fact that this equation in logarithmic coordinates ln *Nu* (ln *Re*) is represented by a straight line. Having plotted the points corresponding to the found pairs of values of the criteria on the graph, straight lines drawn through the pool of points for the modes of every row *i* separately can approximate the equations for those rows. After that, two points for every line has to be chosen, their coordinates Nu_{ai}, Re_{ai} and Nu_{bi}, Re_{bi} are going to be used to find coefficient n_i peculiar to the row:

$$n_i = \frac{\ln\left(Nu_{bi} / Nu_{ai}\right)}{\ln\left(\mathrm{Re}_{bi} / \mathrm{Re}_{ai}\right)}. \tag{14}$$

An example of such a graph with chosen points is shown in Fig. 2.

The shared value of n has to be found as arithmetical mean of n_i

$$n = \sum_{i=1}^{m} n_i \ . \tag{15}$$

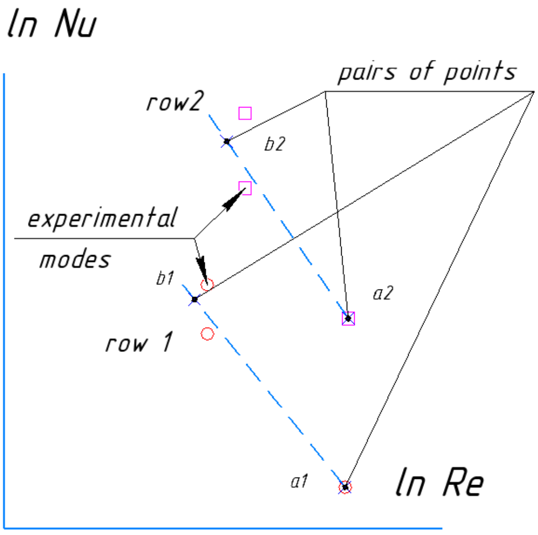

Figure 2 – Example of a criterial equation approximate graph for two tube rows

On the basis of data for arbitrary points of the lines the coefficients C_i for the rows are obtained

$$C_i = \frac{Nu_{ai}}{\mathrm{Re}_{ai}^n}. \tag{16}$$

It's known from the theoretical part of the course that rate of heat transfer starting with third tube row remains almost constant. Taking this into account, the constant C in the equation (7) is assumed to be equal C_6. Then, its correction coefficients have to be found in the following way:

$$E_i = \frac{\sum_{j=1}^{i} C_j}{iC_6}. \tag{17}$$

All obtained equations must be presented in the laboratory work report in an explicit form.

The conclusions to the work must contain comparison of the criterial equations obtained in the work with the ones known from the theoretical part of the course for the processes of forced convection of a cylindrical tube and in a tube bundle, possible reasons of their difference, and explanation how variation of some experimental input values influences or does not the resulting mode of operation of the installation in the dimensionless form.

5. CONTROL QUESTIONS

1. Compare concepts of forced and free convection, as well as reasons for their occurrence.

2. What is heat transfer coefficient, and what physical quantities does it depend on?

3. What differential equations describe the phenomenon of convection?

4. What are the advantages of using the similarity theory in heat engineering over other methods?

5. What similarity criteria are used to describe heat transfer phenomena?

6. What purpose does the lemniscate inlet of wind the tunnel serve? Why the air blower is placed after the tube bundle in the wind tunnel?

7. What is the method of measurement of air velocity with a propeller anemometer?

8. What air flow motion modes had place during experiment?

9. What types of tube bundles are there, compare their qualities.

SOURCES OF ADDITIONAL INFORMATION

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Відповідальний за випуск проф. Антон ГАНЖА

Роботу до видання рекомендував доц. Лариса ТЮТЮННИК

В авторській редакції

План 2021 р. п. 233.
Підписано до друку 13.07.21. Формат 60x84 1/16. Папір друк №2.
Друк – ризографія. Гарнітура Times New Roman. Ум. друк. арк. 0,76.
Обл.-вид. арк. 0,81. Наклад 50 прим. Зам. № . Ціна договірна.

Видавничий центр НТУ «ХПІ».
Свідоцтво про державну реєстрацію ДК № 5478 від 21.08.2017 р.
61002, Харків, вул. Кирпичова, 2

Самостійне електронне видання