

MINISTRY OF EDUCATION AND SCIENCE
NATIONAL TECHNICAL UNIVERSITY
«KHARKIV POLYTECHNIC INSTITUTE»

METHODOLOGICAL INSTRUCTIONS

to calculation assignments

«Thermodynamic and heat transfer processes»

of the course «Theoretical Fundamentals of Heat Engineering»

for students of the specialty

141 «Electric Power Engineering,

Electrical Engineering and Electromechanics»

Kharkiv 2023

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Methodological instructions to calculation assignments «Thermodynamic and heat transfer processes» of the course «Theoretical Fundamentals of Heat Engineering» for students of the specialty 141 – «Electric Power Engineering, Electrical Engineering and Electromechanics» / compiler V.V. Pylyov. – Kharkiv: NTU «KhPI», 2023. – 38 p.

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PREFACE

Principles ruling thermodynamic and heat transfer processes are important to understand for specialists working in all fields of knowledge related to designing and operation of devices and facilities for generation, conversion and transfer of energy. The mandatory assignments of the heat engineering course include three problems:

- finding heat energy consumed by an ideal gas mixture, while it is being heated isochorically and isobarically,
- calculating the thermodynamic parameters of states of an ideal gas during a cyclic process, as well as a work of the gas expansion, the thermal efficiency of the cycle,
- calculating intensity of heat transfer in processes of forced and natural convection using criterial equations, solving the system of heat transfer and energy conservation equations.

These methodological instructions contain tasks and methods of solving the assignments.

Assignments solutions are expected to be given in handwritten form, done legible, and labeled with the student's name, group and variant. Which variant of the task to solve is distributed by the lecturer.

Calculated values must be presented with corresponding units of measurement permitted by International System of Units. The plots in solutions must be drawn keeping scale, their axes designated with titles, units and value labels near the tick marks.

The works failing to meet said requirements are not accepted to be checked.

After an assignment solution having been checked, the lecturer may ask additional theoretical questions related to the assignment topic to determine an appropriate mark. Self-check questions for preliminary making-ready for it are listed after the solving methods.

ASSIGNMENT 1. GAS MIXTURE HEATING

Combustion products consist of carbon dioxide, steam, oxygen, and nitrogen. The mass fractions of listed components are g_{CO_2} , g_{H_2O} , g_{O_2} , g_{N_2} .

Find following values:

- a) volume fractions of the components of the mixture;
- b) apparent molar mass of the mixture;
- c) specific gas constants of the mixture and its components separately;
- d) density of the mixture and its components separately at the standard reference conditions NIST (normal reference conditions ISO 10780, former IUPAC STP);
- e) partial pressures of the components;
- f) heat absorbed by the system per unit mass and unit volume during the processes of heating from temperature t_1 to temperature t_2 at constant pressure and at constant volume.

Initial data to the variants of the task are presented in the table 1.1.

EXAMPLE OF SOLVING OF THE ASSIGNMENT 1

For the purpose of demonstration of the solving order in the example, the following initial data values are used (variant relevant data must be written out from the task table in the actual assignment solution instead):

$$g_{CO_2}=17.9\%, g_{H_2O}=4.3\%, g_{O_2}=5.4\%, g_{N_2}=72.3\%, t_1=1250\text{ }^\circ\text{C}, t_2=400\text{ }^\circ\text{C}. \quad (1.1)$$

Table 1.1 – The Initial data for the assignment 1

| Variant | g_{CO_2} % | g_{H_2O} % | g_{O_2} % | g_{N_2} % | $t_1, ^\circ C$ | $t_2, ^\circ C$ |
|---------|--------------|--------------|-------------|-------------|-----------------|-----------------|
| 1 | 12 | 5 | 9 | 74 | 1260 | 500 |
| 2 | 14 | 3 | 6 | 77 | 1550 | 200 |
| 3 | 17 | 5 | 4 | 74 | 1760 | 300 |
| 4 | 10 | 4 | 10 | 76 | 1300 | 540 |
| 5 | 13 | 8 | 4 | 75 | 1100 | 330 |
| 6 | 12 | 5 | 3 | 80 | 1350 | 300 |
| 7 | 16 | 4 | 4 | 76 | 1400 | 360 |
| 8 | 14 | 2 | 7 | 77 | 1300 | 380 |
| 9 | 14 | 4 | 3 | 79 | 1000 | 350 |
| 10 | 13 | 2 | 7 | 78 | 900 | 280 |
| 11 | 13 | 3 | 5 | 79 | 850 | 200 |
| 12 | 12 | 4 | 6 | 78 | 1050 | 200 |
| 13 | 11 | 2 | 8 | 79 | 750 | 300 |
| 14 | 10 | 4 | 6 | 80 | 1000 | 375 |
| 15 | 15 | 3 | 6 | 76 | 1160 | 400 |
| 16 | 14 | 4 | 5 | 77 | 1000 | 440 |
| 17 | 12 | 8 | 3 | 77 | 1350 | 300 |
| 18 | 11 | 6 | 3 | 80 | 1500 | 345 |
| 19 | 12 | 7 | 5 | 76 | 1225 | 400 |
| 20 | 10 | 5 | 4 | 81 | 1370 | 300 |
| 21 | 13 | 5 | 5 | 77 | 1800 | 340 |
| 22 | 15 | 7 | 1 | 77 | 1520 | 300 |
| 23 | 10 | 6 | 6 | 78 | 1300 | 410 |
| 24 | 14 | 3 | 5 | 78 | 1300 | 320 |
| 25 | 14 | 3 | 7 | 76 | 1470 | 300 |
| 26 | 10 | 5 | 6 | 79 | 1500 | 340 |
| 27 | 11 | 4 | 4 | 81 | 1250 | 400 |
| 28 | 12 | 5 | 7 | 76 | 1400 | 310 |
| 29 | 13 | 6 | 3 | 78 | 1300 | 330 |
| 30 | 14 | 6 | 4 | 76 | 1200 | 540 |

It is expedient to begin solving from finding the apparent molar mass of the mixture, as it simplifies finding volume fractions of the components. The molar masses of the components are required for it. They are obtained using atomic molar masses that are numerically equal to relative atomic masses from periodic table of elements:

$$\mu_C = 12 \text{ kg/kmol}, \mu_H = 1 \text{ kg/kmol}, \mu_O = 16 \text{ kg/kmol}, \mu_N = 14 \text{ kg/kmol}. \quad (1.2)$$

The molar masses of the components:

$$\begin{aligned} \mu_{CO_2} &= 12 + 2 \cdot 16 = 44 \text{ kg/kmol}, \\ \mu_{H_2O} &= 2 \cdot 1 + 16 = 18 \text{ kg/kmol}, \\ \mu_{O_2} &= 2 \cdot 16 = 32 \text{ kg/kmol}, \\ \mu_{N_2} &= 2 \cdot 14 = 28 \text{ kg/kmol}. \end{aligned} \quad (1.3)$$

The mixture apparent molar mass:

$$\mu_{mix} = 1 / \sum_{i=1}^n \frac{g_i}{\mu_i} = 1 / (0.179 / 44 + 0.043 / 18 + 0.054 / 32 + 0.723 / 28) = 29.42 \text{ kg/kmol}. \quad (1.4)$$

The volume fractions of the generic component i and calculating corresponding values for actual components:

$$\begin{aligned} r_i &= \frac{g_i}{\mu_i} \mu_{mix}, \\ r_{CO_2} &= \frac{0.179}{44} 29.42 = 0.12, \\ r_{H_2O} &= \frac{0.043}{18} 29.42 = 0.07, \\ r_{O_2} &= \frac{0.054}{32} 29.42 = 0.05, \end{aligned} \quad (1.5)$$

$$r_{N_2} = \frac{0.723}{28} 29.42 = 0.76 .$$

A check to ascertain if the total of the new-found volume fractions of the components equals one:

$$r_{mix} = \sum_{i=1}^n r_i = 0.12 + 0.04 + 0.05 + 0.76 = 0.97 \approx 1 . \quad (1.6)$$

Specific gas constants can be determined using the formula

$$R = \frac{R_0}{\mu} , \quad (1.7)$$

where $R_0 = 8314 \text{ J}/(\text{kg} \cdot \text{kmol})$ is the universal ideal gas constant.

The values of specific gas constants for the mixture and its components are:

$$\begin{aligned} R_{mix} &= \frac{R_0}{\mu_{mix}} = \frac{8314}{29.42} = 283 \text{ J}/(\text{kg} \cdot \text{K}), \\ R_{CO_2} &= \frac{R_0}{\mu_{CO_2}} = \frac{8314}{44} = 189 \text{ J}/(\text{kg} \cdot \text{K}), \\ R_{H_2O} &= \frac{R_0}{\mu_{H_2O}} = \frac{8314}{18} = 462 \text{ J}/(\text{kg} \cdot \text{K}), \\ R_{O_2} &= \frac{R_0}{\mu_{O_2}} = \frac{8314}{32} = 260 \text{ J}/(\text{kg} \cdot \text{K}), \\ R_{N_2} &= \frac{R_0}{\mu_{N_2}} = \frac{8314}{28} = 297 \text{ J}/(\text{kg} \cdot \text{K}). \end{aligned} \quad (1.8)$$

The standard reference conditions NIST are temperature $T_0 = 273.15 \text{ K}$ and pressure $p_0 = 1.013 \cdot 10^5 \text{ Pa}$. The corresponding molar volume of any gas at this state equals $V_{m0} = 22.4 \text{ m}^3/\text{kmol}$. The density of a gas can be found as

$$\rho = \frac{\mu}{V_{m0}}. \quad (1.9)$$

The values of density for the mixture and its components are:

$$\begin{aligned} \rho_{mix} &= \frac{\mu_{mix}}{V_{m0}} = \frac{29.42}{22.4} = 1.32 \text{ kg/m}^3, \\ \rho_{CO_2} &= \frac{\mu_{CO_2}}{V_{m0}} = \frac{44}{22.4} = 1.97 \text{ kg/m}^3, \\ \rho_{H_2O} &= \frac{\mu_{H_2O}}{V_{m0}} = \frac{18}{22.4} = 0.8 \text{ kg/m}^3, \\ \rho_{O_2} &= \frac{\mu_{O_2}}{V_{m0}} = \frac{32}{22.4} = 1.43 \text{ kg/m}^3, \\ \rho_{N_2} &= \frac{\mu_{N_2}}{V_{m0}} = \frac{28}{22.4} = 1.25 \text{ kg/m}^3. \end{aligned} \quad (1.10)$$

Partial pressures of the components at the standard reference conditions
NIST:

$$\begin{aligned} P_{CO_2} &= P_0 \cdot r_{CO_2} = 1.013 \cdot 10^5 \cdot 0.12 = 0.12156 \cdot 10^5 \text{ Pa}, \\ P_{H_2O} &= P_0 \cdot r_{H_2O} = 1.013 \cdot 10^5 \cdot 0.07 = 0.07091 \cdot 10^5 \text{ Pa}, \\ P_{O_2} &= P_0 \cdot r_{O_2} = 1.013 \cdot 10^5 \cdot 0.05 = 0.05065 \cdot 10^5 \text{ Pa}, \\ P_{N_2} &= P_0 \cdot r_{N_2} = 1.013 \cdot 10^5 \cdot 0.76 = 0.76988 \cdot 10^5 \text{ Pa}. \end{aligned} \quad (1.11)$$

A check to ascertain if the total of the partial pressures of the components equals the standard pressure:

$$P_0 = \sum_{i=1}^n P_i = (0.12156 + 0.07091 + 0.05065 + 0.6988) \cdot 10^5 \approx 1.013 \cdot 10^5 \text{ Pa}. \quad (1.12)$$

All the following formulae for finding heat absorbed by a system require knowledge of certain heat capacities values. They must be found using table data in the appendix separately for every of mixture components.

Heat absorbed by a system per unit mass during the processes of heating from t_1 to t_2 under constant pressure:

$$q_p = \sum_{i=1}^n (c_{pm_i} \cdot g_i) \cdot t_2 - \sum_{i=1}^n (c_{pm_i} \cdot g_i) \cdot t_1, \quad (1.13)$$

where c_{pm} is a mean specific heat capacity at a constant pressure.

Heat absorbed by a system per unit mass during the processes of heating from t_1 to t_2 under constant volume:

$$q_v = \sum_{i=1}^n (c_{vm_i} \cdot g_i) \cdot t_2 - \sum_{i=1}^n (c_{vm_i} \cdot g_i) \cdot t_1, \quad (1.14)$$

where c_{vm} is a mean specific heat capacity at a constant volume.

Heat absorbed by a system per unit volume during the processes of heating from t_1 to t_2 under constant pressure:

$$q'_p = \sum_{i=1}^n (c'_{pm_i} \cdot r_i) \cdot t_2 - \sum_{i=1}^n (c'_{pm_i} \cdot r_i) \cdot t_1, \quad (1.15)$$

where c'_{pm} is a mean volume heat capacity at a constant pressure.

Heat absorbed by a system per unit volume during the processes of heating from t_1 to t_2 under constant volume:

$$q'_v = \sum_{i=1}^n (c'_{vm_i} \cdot r_i) \cdot t_2 - \sum_{i=1}^n (c'_{vm_i} \cdot r_i) \cdot t_1, \quad (1.16)$$

where c'_{vm} is a mean volume heat capacity at a constant volume.

Values for each of the mentioned heat capacities for temperatures of the beginning and the end of processes t_1 and t_2 are taken from the tables A.1-A.4 of the appendix and used for forming the table 1.2.

Table 1.2 – The values of heat capacities in the example

| | $t_2 = 400\text{ }^{\circ}\text{C}$ | | | | $t_1 = 1250\text{ }^{\circ}\text{C}$ | | | |
|--------------------------------------|-------------------------------------|------------------|----------------|----------------|--------------------------------------|------------------|----------------|----------------|
| | CO ₂ | H ₂ O | O ₂ | N ₂ | CO ₂ | H ₂ O | O ₂ | N ₂ |
| c_{pm} , kJ/(kg K) | 0,9826 | 1,9477 | 0,9651 | 1,0567 | <u>1,1595</u> | 2,2268 | 1,05445 | 1,1403 |
| c_{vm} , kJ/(kg K) | 0,7938 | 1,4863 | 0,7051 | 0,7599 | 0,9705 | 1,7652 | 0,79485 | 0,84365 |
| c'_{pm} , kJ/(m ³ K) | 1,9297 | 1,5654 | 1,3775 | 1,3205 | 2,2768 | 1,78985 | 1,50555 | 1,4254 |
| c'_{vm} , kJ/(m ³ K) | 1,5587 | 1,1945 | 1,0065 | 0,9496 | 1,90585 | 1,4189 | 1,1346 | 1,0545 |

In a case if the value of one of the needed temperatures does not coincide with any data point in tables of the appendix exactly, like at $t_1=1250\text{ }^{\circ}\text{C}$ in present example, sixteen corresponding heat capacities must be found by interpolation using general formula

$$C^x = (C^a - C^b) (t_x - t_b) / (t_a - t_b) + C^b, \quad (1.17)$$

where t_a and t_b are the closest higher and lower temperatures, for which data points are known;

t_x is the temperature of interest,

C^a , C^b and C^x are corresponding heat capacities.

For example, the underlined value in the table is calculated as follows:

$$c_{pmCO_2}^{1250} = (c_{pmCO_2}^{1300} - c_{pmCO_2}^{1200})(1250 - 1200)/(1300 - 1200) + c_{pmCO_2}^{1200} =$$

$$= (1.1660 - 1.1530)(1250 - 1200)/(1300 - 1200) + 1.1530 = 1.1595 \text{ kJ/(kg K)}. \quad (1.18)$$

Fifteen others heat capacities are calculated in the similar way.

Then absorbed heats can be found, if data from the table 1.2 being substituted in the formulas (1.13)–(1.16):

$$q_p = \left(c_{pmCO_2} \Big|_0^{t_2} \cdot g_{CO_2} + c_{pmH_2O} \Big|_0^{t_2} \cdot g_{H_2O} + c_{pmO_2} \Big|_0^{t_2} \cdot g_{O_2} + c_{pmN_2} \Big|_0^{t_2} \cdot g_{N_2} \right) \cdot t_2 -$$

$$- \left(c_{pmCO_2} \Big|_0^{t_1} \cdot g_{CO_2} + c_{pmH_2O} \Big|_0^{t_1} \cdot g_{H_2O} + c_{pmO_2} \Big|_0^{t_1} \cdot g_{O_2} + c_{pmN_2} \Big|_0^{t_1} \cdot g_{N_2} \right) \cdot t_1 =$$

$$= (0.9826 \cdot 0.179 + 1.9477 \cdot 0.043 + 0.9651 \cdot 0.054 + 1.0567 \cdot 0.723) \cdot 400 -$$

$$- (1.1595 \cdot 0.179 + 2.2268 \cdot 0.043 + 1.05445 \cdot 0.05 + 1.1403 \cdot 0.723) \cdot 1250 = \quad (1.19)$$

$$= -1051 \text{ kJ/kg},$$

$$q_v = \left(c_{vmCO_2} \Big|_0^{t_2} \cdot g_{CO_2} + c_{vmH_2O} \Big|_0^{t_2} \cdot g_{H_2O} + c_{vmO_2} \Big|_0^{t_2} \cdot g_{O_2} + c_{vmN_2} \Big|_0^{t_2} \cdot g_{N_2} \right) \cdot t_2 -$$

$$- \left(c_{vmCO_2} \Big|_0^{t_1} \cdot g_{CO_2} + c_{vmH_2O} \Big|_0^{t_1} \cdot g_{H_2O} + c_{vmO_2} \Big|_0^{t_1} \cdot g_{O_2} + c_{vmN_2} \Big|_0^{t_1} \cdot g_{N_2} \right) \cdot t_1 =$$

$$= (0.7938 \cdot 0.179 + 1.4863 \cdot 0.043 + 0.7051 \cdot 0.054 + 0.7599 \cdot 0.723) \cdot 400 -$$

$$- (0.9705 \cdot 0.179 + 1.7652 \cdot 0.043 + 0.79485 \cdot 0.054 + 0.84365 \cdot 0.723) \cdot 1250 = \quad (1.20)$$

$$= -808 \text{ kJ/kg},$$

$$q'_p = \left(c'_{pmCO_2} \Big|_0^{t_2} \cdot r_{CO_2} + c'_{pmH_2O} \Big|_0^{t_2} \cdot r_{H_2O} + c'_{pmO_2} \Big|_0^{t_2} \cdot r_{O_2} + c'_{pmN_2} \Big|_0^{t_2} \cdot r_{N_2} \right) \cdot t_2 -$$

$$- \left(c'_{pmCO_2} \Big|_0^{t_1} \cdot r_{CO_2} + c'_{pmH_2O} \Big|_0^{t_1} \cdot r_{H_2O} + c'_{pmO_2} \Big|_0^{t_1} \cdot r_{O_2} + c'_{pmN_2} \Big|_0^{t_1} \cdot r_{N_2} \right) \cdot t_1 =$$

$$= (1.9297 \cdot 0.12 + 1.5654 \cdot 0.07 + 1.3775 \cdot 0.05 + 1.3205 \cdot 0.76) \cdot 400 -$$

$$- (2.2768 \cdot 0.12 + 1.78985 \cdot 0.07 + 1.50555 \cdot 0.05 + 1.4254 \cdot 0.76) \cdot 1250 = \quad (1.21)$$

$$= -1380 \text{ kJ/m}^3,$$

$$\begin{aligned}
q'_v &= \left(c'_{vmCO_2} \Big|_0^{t_2} \cdot r_{CO_2} + c'_{vmH_2O} \Big|_0^{t_2} \cdot r_{H_2O} + c'_{vmO_2} \Big|_0^{t_2} \cdot r_{O_2} + c'_{vmN_2} \Big|_0^{t_2} \cdot r_{N_2} \right) \cdot t_2 - \\
&- \left(c'_{vmCO_2} \Big|_0^{t_1} \cdot r_{CO_2} + c'_{vmH_2O} \Big|_0^{t_1} \cdot r_{H_2O} + c'_{vmO_2} \Big|_0^{t_1} \cdot r_{O_2} + c'_{vmN_2} \Big|_0^{t_1} \cdot r_{N_2} \right) \cdot t_1 = \\
&= (1,5587 \cdot 0,12 + 1,1945 \cdot 0,07 + 1,0065 \cdot 0,05 + 0,9496 \cdot 0,76) \cdot 400 - \\
&- (1,90585 \cdot 0,12 + 1,4189 \cdot 0,07 + 1,1346 \cdot 0,05 + 1,0545 \cdot 0,76) \cdot 1250 = \quad (1.22) \\
&= -1071 \text{ kJ/m}^3.
\end{aligned}$$

SELF-CHECK QUESTIONS FOR THE ASSIGNMENT 1

1. How can the composition of a gas mixture be specified?
2. What are average and true heat capacities?
3. What is a partial pressure of a gas in a mixture?
4. Formulate Dalton's law for a mixture of gases.
5. How are isobaric and isochoric heat capacities of a substance related?
6. What is the relation between specific volume, density, molar mass, gas constant, and pressure of a gas?

ASSIGNMENT 2. THERMODYNAMIC CYCLE

Subsequent isothermal, isochoric, adiabatic, and isobaric processes are combined into a cycle with air as a working medium, as Fig. 2.1 represents.

Find following values:

- a) thermal properties of working medium (pressure p , specific volume v , and thermodynamic temperature T) at the characteristic points of the cycle (states 1, 2, 3, and 4 in Fig. 2.1);
- b) the work produced with 1 kg of air in the one cycle, as algebraic sum of the works performed during the processes separately;
- c) the heat absorbed by 1 kg of air in the one cycle as algebraic sum of the heats absorbed during the processes separately;
- d) thermal efficiency of the cycle;

f) draw the obtained cycle in pressure / specific volume and temperature / specific entropy charts.

Assume the isobaric specific heat capacity of air to be constant $c_p = 1 \text{ kJ}/(\text{kg}\cdot\text{K})$.

Initial data to the variants of the task are presented in the table 2.1.

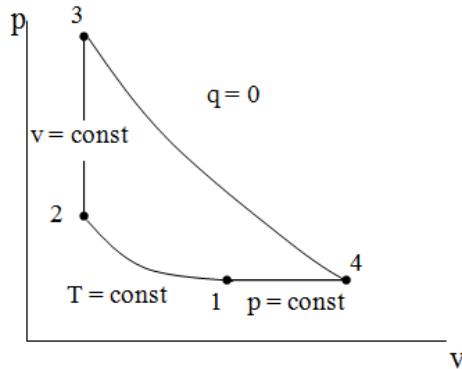


Figure 2.1 – Pressure / specific volume diagram of the thermodynamic cycle

EXAMPLE OF SOLVING OF THE ASSIGNMENT 2

For the purpose of demonstration of the solving order in the example, the following initial data values are used (variant relevant data must be written out from the task table in the actual assignment solution instead):

$$p_1 = 1.2 \text{ bar}, t_1 = 77 \text{ }^{\circ}\text{C}, v_2 = 0.4 \text{ m}^3/\text{kg}, p_3 = 12 \text{ bar}. \quad (2.1)$$

Specific gas constant of air is $R = 287 \text{ kJ}/(\text{kg}/\text{K})$.

The isochoric heat capacity of air can be found from the Mayer's relation

$$c_v = c_p - R = 1000 - 287 = 713 \text{ kJ}/(\text{kg}/\text{K}). \quad (2.2)$$

Table 2.1 – The Initial data for the assignment 2

| Variant | Known properties | | | |
|---------|--------------------------|------------------------------------|------------------------------------|----------------------------|
| 1 | $p_1 = 1 \text{ bar}$ | $t_1 = 27^\circ\text{C}$ | $p_2 = 5 \text{ bar}$ | $p_3 = 14 \text{ bar}$ |
| 2 | $p_1 = 3.1 \text{ bar}$ | $t_1 = 72^\circ\text{C}$ | $v_2 = 0.16 \text{ m}^3/\text{kg}$ | $p_3 = 33 \text{ bar}$ |
| 3 | $p_1 = 1 \text{ bar}$ | $t_1 = 20^\circ\text{C}$ | $p_2 = 5 \text{ bar}$ | $t_3 = 700^\circ\text{C}$ |
| 4 | $p_1 = 1.6 \text{ bar}$ | $v_1 = 3.7 \text{ m}^3/\text{kg}$ | $v_2 = 0.75 \text{ m}^3/\text{kg}$ | $t_3 = 3300^\circ\text{C}$ |
| 5 | $t_1 = 20^\circ\text{C}$ | $v_1 = 1 \text{ m}^3/\text{kg}$ | $p_2 = 8 \text{ bar}$ | $p_3 = 30 \text{ bar}$ |
| 6 | $p_1 = 3 \text{ bar}$ | $v_1 = 0,3 \text{ m}^3/\text{kg}$ | $p_2 = 8 \text{ bar}$ | $p_3 = 20 \text{ bar}$ |
| 7 | $p_1 = 1 \text{ bar}$ | $t_1 = 50^\circ\text{C}$ | $p_2 = 3 \text{ bar}$ | $p_3 = 12 \text{ bar}$ |
| 8 | $p_1 = 1.2 \text{ bar}$ | $t_1 = 65^\circ\text{C}$ | $v_2 = 0.5 \text{ m}^3/\text{kg}$ | $t_3 = 1650^\circ\text{C}$ |
| 9 | $p_1 = 1.5 \text{ bar}$ | $t_1 = 74^\circ\text{C}$ | $v_2 = 0.6 \text{ m}^3/\text{kg}$ | $t_3 = 1550^\circ\text{C}$ |
| 10 | $p_1 = 1.6 \text{ bar}$ | $t_1 = 80^\circ\text{C}$ | $v_2 = 0.45 \text{ m}^3/\text{kg}$ | $t_3 = 1600^\circ\text{C}$ |
| 11 | $p_1 = 4 \text{ bar}$ | $t_1 = 40^\circ\text{C}$ | $p_2 = 8.5 \text{ bar}$ | $p_3 = 265 \text{ bar}$ |
| 12 | $p_1 = 5 \text{ bar}$ | $t_1 = 20^\circ\text{C}$ | $p_2 = 12 \text{ bar}$ | $p_3 = 30 \text{ bar}$ |
| 13 | $p_1 = 6 \text{ bar}$ | $t_1 = 30^\circ\text{C}$ | $p_2 = 18 \text{ bar}$ | $p_3 = 48 \text{ bar}$ |
| 14 | $p_1 = 3 \text{ bar}$ | $t_1 = 50^\circ\text{C}$ | $p_2 = 16 \text{ bar}$ | $p_3 = 60 \text{ bar}$ |
| 15 | $p_1 = 1.1 \text{ bar}$ | $t_1 = 80^\circ\text{C}$ | $p_2 = 2.2 \text{ bar}$ | $t_4 = 600^\circ\text{C}$ |
| 16 | $p_1 = 1.3 \text{ bar}$ | $t_1 = 70^\circ\text{C}$ | $p_2 = 3 \text{ bar}$ | $t_4 = 640^\circ\text{C}$ |
| 17 | $p_1 = 1.5 \text{ bar}$ | $t_1 = 60^\circ\text{C}$ | $p_2 = 3.2 \text{ bar}$ | $t_4 = 460^\circ\text{C}$ |
| 18 | $p_1 = 1.7 \text{ bar}$ | $t_1 = 50^\circ\text{C}$ | $p_2 = 4 \text{ bar}$ | $t_4 = 680^\circ\text{C}$ |
| 19 | $p_1 = 1.8 \text{ bar}$ | $t_1 = 40^\circ\text{C}$ | $p_2 = 3.8 \text{ bar}$ | $t_4 = 700^\circ\text{C}$ |
| 20 | $p_1 = 2 \text{ bar}$ | $t_1 = 30^\circ\text{C}$ | $p_2 = 5.5 \text{ bar}$ | $t_4 = 720^\circ\text{C}$ |
| 21 | $p_1 = 3 \text{ bar}$ | $v_1 = 0.3 \text{ m}^3/\text{kg}$ | $p_2 = 8 \text{ bar}$ | $p_3 = 20 \text{ bar}$ |
| 22 | $p_1 = 4 \text{ bar}$ | $v_1 = 0.25 \text{ m}^3/\text{kg}$ | $p_2 = 10 \text{ bar}$ | $p_3 = 25 \text{ bar}$ |
| 23 | $p_1 = 5 \text{ bar}$ | $v_1 = 0.2 \text{ m}^3/\text{kg}$ | $p_2 = 10 \text{ bar}$ | $p_3 = 30 \text{ bar}$ |
| 24 | $p_1 = 6 \text{ bar}$ | $v_1 = 0.2 \text{ m}^3/\text{kg}$ | $p_2 = 9 \text{ bar}$ | $p_3 = 35 \text{ bar}$ |
| 25 | $p_1 = 1 \text{ bar}$ | $t_1 = 120^\circ\text{C}$ | $p_2 = 5 \text{ bar}$ | $t_4 = 400^\circ\text{C}$ |
| 26 | $p_1 = 1.2 \text{ bar}$ | $t_1 = 100^\circ\text{C}$ | $p_2 = 6 \text{ bar}$ | $t_4 = 380^\circ\text{C}$ |
| 27 | $p_1 = 1.4 \text{ bar}$ | $t_1 = 80^\circ\text{C}$ | $p_2 = 4 \text{ bar}$ | $t_4 = 320^\circ\text{C}$ |
| 28 | $p_1 = 1.1 \text{ bar}$ | $t_1 = 120^\circ\text{C}$ | $p_2 = 3.1 \text{ bar}$ | $t_4 = 630^\circ\text{C}$ |
| 29 | $p_1 = 1.5 \text{ bar}$ | $t_1 = 125^\circ\text{C}$ | $p_2 = 3.2 \text{ bar}$ | $t_4 = 450^\circ\text{C}$ |
| 30 | $p_1 = 1.2 \text{ bar}$ | $t_1 = 115^\circ\text{C}$ | $p_2 = 4.1 \text{ bar}$ | $t_4 = 670^\circ\text{C}$ |

Adiabatic index of air is

$$k = c_p / c_v = 1000 / 713 \approx 1,4. \quad (2.3)$$

Parameters of one state (cycle point) are related to another one's by the main gas equation

$$p \cdot v = R \cdot T. \quad (2.4)$$

Using this equation and ones of thermodynamic processes, thermal properties of working medium (p, v, T) at the characteristic points of the cycle (1, 2, 3, 4) must be found. The set of properties to calculate depends on which of them are already known from initial data. So, the following algorithm of solving is going to be slightly different from the one specific to actual variant data, which can be obtained with formula manipulations in all cases.

For the points 1 and 2 in isothermal process temperatures are

$$T_2 = T_1 = t_1 + 273 = 77 + 273 = 350 \text{ K} . \quad (2.5)$$

From (2.4) specific volume at points 1:

$$v_1 = \frac{RT_1}{p_1} = \frac{287 \cdot 350}{1,2 \cdot 10^5} = 0,837 \text{ m}^3/\text{kg}. \quad (2.6)$$

The equation of an isothermal process is $p \cdot v = const$. For process 1-2 it can be written as

$$p_1 v_1 = p_2 v_2 , \quad (2.7)$$

therefore, pressure for the point 2 is

$$p_2 = \frac{p_1 v_1}{v_2} = \frac{1.2 \cdot 10^5 \cdot 0.837}{0.4} = 2.511 \cdot 10^5 \text{ Pa.} \quad (2.8)$$

Since 2-3 is isochoric process,

$$v_2 = v_3 = 0.4 \text{ m}^3/\text{kg}. \quad (2.9)$$

The equation of the isochoric process 2-3 is

$$\frac{P_2}{P_3} = \frac{T_2}{T_3}, \quad (2.10)$$

therefore, temperature at the point 3 is

$$T_3 = \frac{p_3 \cdot T_2}{p_2} = \frac{12 \cdot 10^5 \cdot 350}{2.511 \cdot 10^5} = 1673 \text{ K.} \quad (2.11)$$

The process 4-1 is isobaric, so pressure in the course of it remains constant:

$$p_4 = p_1 = 120 \text{ kPa.} \quad (2.12)$$

The process 3-4 is adiabatic. Its equation is

$$p_3 v_3^k = p_4 v_4^k, \quad (2.13)$$

therefore, specific volume for the point 4 is

$$v_4 = v_3 \left(\frac{p_3}{p_4} \right)^{1/1.4} = 0.4 \cdot \left(\frac{12 \cdot 10^5}{1.2 \cdot 10^5} \right)^{1/1.4} = 2.07 \text{ m}^3/\text{kg}. \quad (2.14)$$

The isobarical process 4-1 equation is

$$\frac{v_1}{v_4} = \frac{T_1}{T_4}, \quad (2.15)$$

therefore, temperature for the point 3 is

$$T_4 = \frac{350 \cdot 2.07}{0.837} = 866 \text{ K}. \quad (2.16)$$

The work of the isothermal process 1-2 (in which compression occurs – volume decreases, pressure increases) is less than zero, since the work is performed over the working medium:

$$l_{1-2} = RT_1 \ln \frac{v_2}{v_1} = 287 \cdot 350 \ln \frac{0.4}{0.837} = -74.168 \text{ kJ/kg}. \quad (2.17)$$

The work of the isochoric process 2-3 is zero, since there is no change in volume :

$$l_{2-3} = 0 \text{ kJ/kg}. \quad (2.18)$$

The work of the adiabatic process 3-4:

$$l_{3-4} = \frac{R}{k-1} (T_3 - T_4) = \frac{287}{1.4-1} (1673 - 866) = 579.022 \text{ kJ/kg}. \quad (2.19)$$

The work of the isobarical process:

$$l_{4-1} = p_4(v_1 - v_4) = 1.2 \cdot 10^5 (0.837 - 2.07) = -147.96 \text{ kJ/kg}. \quad (2.20)$$

The work of the cycle is the algebraic sum of the works of the processes forming the cycle:

$$l_c = l_{1-2} + l_{2-3} + l_{3-4} + l_{4-1} = -74.168 + 0 + 579.022 - 147.96 = 357 \text{ kJ/kg.} \quad (2.21)$$

In an isothermal process, the heat absorbed during the processes is equal to the work of the process:

$$q_{1-2} = l_{1-2} = -74,168 \text{ kJ/kg.} \quad (2.22)$$

The heat absorbed during the isochoric process:

$$q_{2-3} = c_v(T_3 - T_2) = 0.713(1673 - 350) = 943.299 \text{ kJ/kg.} \quad (2.23)$$

The heat absorbed during the adiabatic process is zero by definition:

$$q_{3-4} = 0 \text{ kJ/kg.} \quad (2.24)$$

The heat absorbed during the isobarical process:

$$q_{4-1} = c_p(T_1 - T_4) = 1(350 - 866) = -516 \text{ kJ/kg.} \quad (2.25)$$

The heat absorbed during the cycle is equal to the algebraic sum of the heats absorbed during the processes forming the cycle:

$$q_c = q_{1-2} + q_{2-3} + q_{3-4} + q_{4-1} = -74.168 + 943.299 + 0 - 516 = 354 \text{ kJ/kg.} \quad (2.26)$$

According to the principle of equivalence of heat and mechanical work of the cycle, the heat absorbed during the cycle is equal to the work produced during

the cycle $l_c \cong q_c$. Their disparity, originating in errors of calculating, should not be more than 5% of lesser of the values:

$$\delta = \frac{l_c - q_c}{q_c} = \frac{357 - 354}{354} = 0.0085. \quad (2.27)$$

Thermal efficiency of the cycle :

$$\eta = \frac{\ell_c}{q_{pos}}, \quad (2.28)$$

where q_{pos} is the positive heat absorbed by the working medium in the processes of the cycle (i.e., the sum of those heats that more than zero). In this case, heat of the process 2-3 is the only heat that is positive in this cycle. Hence, thermal efficiency value is

$$\eta = \frac{\ell_c}{q_{2-3}} = \frac{357}{943.299} = 0.3785. \quad (2.29)$$

It is necessary to determine the value of specific entropy at the characteristic points of the cycle to plot in the T - s diagram. It can be calculated using equation

$$s = c_p \ln \frac{T}{T_{stp}} - R \ln \frac{p}{p_{stp}}, \quad (2.30)$$

where $T_{stp} = 273 \text{ K}$, $p_{stp} = 1.013 \cdot 10^5 \text{ Pa}$ are the temperature and pressure of the standard reference conditions NIST.

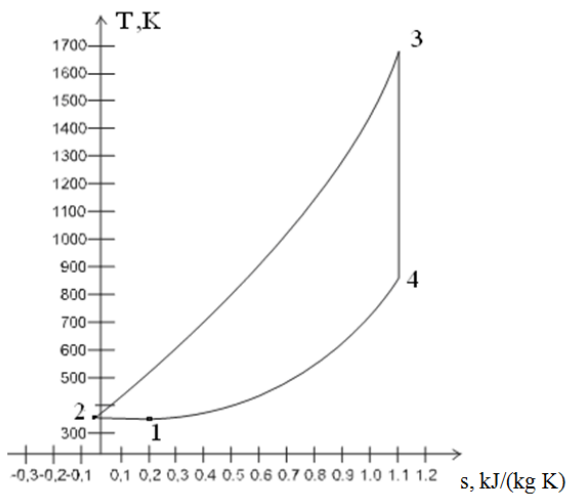
The values of specific entropy at the characteristic points are:

$$\begin{aligned}
s_1 &= c_p \ln \frac{T_1}{T_{stp}} - R \ln \frac{p_1}{p_{stp}} = 1 \ln \frac{350}{273} - 0.287 \ln \frac{1.2 \cdot 10^5}{1.013 \cdot 10^5} = 0.2 \text{ kJ/(kg K)}, \\
s_2 &= c_p \ln \frac{T_2}{T_{stp}} - R \ln \frac{p_2}{p_{stp}} = 1 \ln \frac{350}{273} - 0.287 \ln \frac{2.511 \cdot 10^5}{1.013 \cdot 10^5} = -0.012 \text{ kJ/(kg K)}, \\
s_3 &= c_p \ln \frac{T_3}{T_{stp}} - R \ln \frac{p_3}{p_{stp}} = 1 \ln \frac{1673}{273} - 0.287 \ln \frac{12 \cdot 10^5}{1.013 \cdot 10^5} = 1.1 \text{ kJ/(kg K)}, \\
s_4 &= c_p \ln \frac{T_4}{T_{stp}} - R \ln \frac{p_4}{p_{stp}} = 1 \ln \frac{866}{273} - 0.287 \ln \frac{1.2 \cdot 10^5}{1.013 \cdot 10^5} = 1.1 \text{ kJ/(kg K)}.
\end{aligned}
\tag{2.31}$$

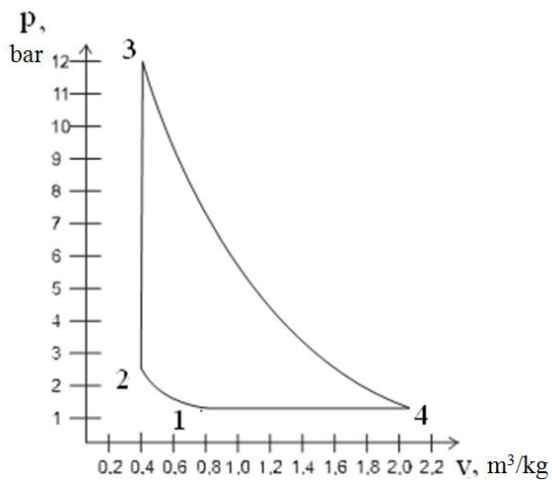
Having obtained all the necessary data (2.5)-(2.16), (2.31), the charts in pressure / specific volume p - v and temperature / specific entropy T - s can be plotted. For the data of the present example they look like shown in Fig. 2.2.

SELF-CHECK QUESTIONS FOR THE ASSIGNMENT 2

1. What is an ideal gas? What is the main equation of gas state?
2. What is a specific gas constant and the universal gas constant?
3. What is meant by the term internal energy? What does a change in the internal energy of an ideal gas depend on?
4. What is an entropy change in any reversible thermodynamic process? How the heat of the process is graphically represented?
5. What is thermal efficiency of a cycle? What values can it acquire?
6. Formulate the essence of the first law of thermodynamics. What are its mathematical expressions?
7. What is a polytropic processes? Are there such processes in present assignment?



a



b

Figure 2.2 – Examples of the thermodynamic cycle charts:
a – temperature / specific entropy diagram;
b – pressure / specific volume diagram

ASSIGNMENT 3. HEAT TRANSFER

There is a flow of transformer oil with velocity W in the aluminum horizontal pipe, which has inner and outer diameters d_{int}/d_{out} . The temperatures of oil at the inlet and the outlet are t_1 and t_2 . The pipe is contained in the tranquil water with temperature t_w . Find the pipe length.

Initial data to the variants of the task are presented in the table 3.1.

EXAMPLE OF SOLVING OF THE ASSIGNMENT 3

For the purpose of demonstration of the solving order in the example, the following initial data values are used (variant relevant data must be written out from the task table in the actual assignment solution instead):

$$d_{int} = 40 \text{ mm}, d_{out} = 42 \text{ mm}, W = 1.2 \text{ m/s}, t_1 = 65 \text{ }^\circ\text{C}, t_2 = 60 \text{ }^\circ\text{C}, t_w = 10 \text{ }^\circ\text{C}. \quad (3.1)$$

The heat transfer scheme in this problem is presented in Fig. 1.

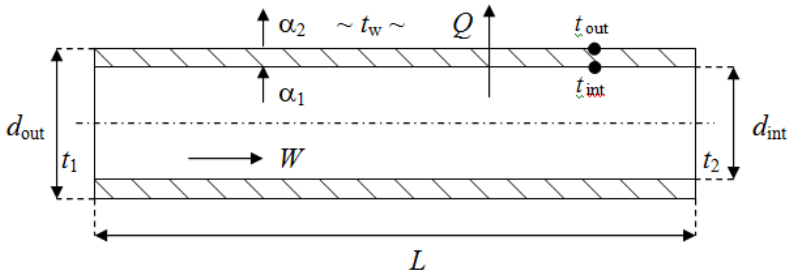


Figure 3.1 – Heat transfer scheme, initial data, unknown quantities

The sought tube length L can be found from the heat balance equation. The change in enthalpy of the oil flow passing through the tube must be equal to the heat flow transmitted from the oil to the cooling water surrounding the tube:

Table 3.1 – The Initial data for the assignment 3

| Variant | d_{out} , mm | d_{inv} , mm | t_1 , °C | t_2 , °C | W m/s | t_w , °C |
|---------|-------------------|-------------------|------------|------------|------------|------------|
| 1 | 45 | 41 | 75 | 70 | 1.5 | 15 |
| 2 | 32 | 29 | 62 | 58 | 1.8 | 13 |
| 3 | 40 | 36 | 68 | 63 | 2.2 | 10 |
| 4 | 34 | 30 | 80 | 76 | 1.2 | 18 |
| 5 | 50 | 46 | 63 | 58 | 0.7 | 16 |
| 6 | 30 | 28 | 45 | 40 | 0.5 | 15 |
| 7 | 34 | 32 | 55 | 50 | 1.7 | 13 |
| 8 | 22 | 21 | 60 | 51 | 0.5 | 12 |
| 9 | 36 | 34 | 76 | 70 | 0.6 | 12 |
| 10 | 40 | 38 | 80 | 76 | 1.7 | 12 |
| 11 | 32 | 30 | 70 | 66 | 0.8 | 15 |
| 12 | 28 | 27 | 80 | 75 | 1.0 | 10 |
| 13 | 25 | 24 | 77 | 72 | 0.2 | 8 |
| 14 | 28 | 26 | 70 | 67 | 1.5 | 18 |
| 15 | 45 | 41 | 60 | 55 | 1.2 | 15 |
| 16 | 48 | 44 | 55 | 50 | 1.1 | 11 |
| 17 | 50 | 46 | 50 | 45 | 2.0 | 10 |
| 18 | 25 | 24 | 58 | 52 | 3.0 | 15 |
| 19 | 42 | 38 | 68 | 64 | 0.9 | 18 |
| 20 | 45 | 41 | 83 | 78 | 1.1 | 10 |
| 21 | 34 | 30 | 68 | 63 | 1.2 | 12 |
| 22 | 25 | 24 | 63 | 57 | 0.4 | 10 |
| 23 | 50 | 46 | 87 | 69 | 0.6 | 15 |
| 24 | 45 | 41 | 55 | 50 | 1,5 | 0 |
| 25 | 22 | 21 | 55 | 50 | 0.2 | 17 |
| 26 | 44 | 42 | 60 | 55 | 1.9 | 12 |
| 27 | 25 | 21 | 55 | 50 | 1.7 | 16 |
| 28 | 28 | 26 | 45 | 35 | 0.6 | 28 |
| 29 | 34 | 32 | 70 | 65 | 0.5 | 15 |
| 30 | 42 | 38 | 73 | 68 | 2.3 | 10 |

$$G_o c_{po} (t_1 - t_2) = k_l (\bar{t}_o - t_w) L, \quad (3.2)$$

where the oil flow rate is

$$G_o = \rho_o \cdot W f_{int}, \quad (3.3)$$

$$f_{int} = \pi d_{int}^2 / 4 = \pi 0.04^2 / 4 = 0.00126 \text{ m}^2 \quad (3.4)$$

is the inner cross section of the tube,

c_{po} and ρ_o are heat capacity and density of oil at mean oil temperature

$$\bar{t}_o = (t_1 + t_2) / 2 = (65 + 60) / 2 = 62.5 \text{ }^\circ\text{C}, \quad (3.5)$$

k_l is the heat transfer coefficient per unit length of the tube, which in turn, can be found as

$$k_l = \frac{\pi}{\frac{1}{\alpha_1 d_{int}} + \frac{1}{\alpha_2 d_{out}} + \frac{1}{2\lambda_{al}} \ln \frac{d_{out}}{d_{int}}}. \quad (3.6)$$

To calculate this parameter, it is necessary to ascertain the heat emission coefficients from oil to the tube wall α_1 and from the tube wall to water α_2 .

Heat conductivity of aluminum is assumed constant $\lambda_{al} = 230 \text{ W/(m}\cdot\text{K)}$.

Thermalphysical parameters of oil and water, on the other hand, depend on their temperature. So, to find c_{po} and ρ_o above, as well as other significant quantities, table data is applied. Properties of oil are supposed to be taken from the table A.5 in the appendix, properties of water from table A.6.

In the cases of the value of one of the needed temperatures does not coincide with any data point in tables of the appendix exactly, like temperature (3.5) in present example, values of properties of oil must be found by interpolation

using general formula (1.17), as was done with heat capacities in the assignment 1.

For example, oil density is calculated as follows:

$$\rho_o = (874 - 880)/(70 - 60) \cdot (62.5 - 60) + 880 = 854.5 \text{ kg/m}^3. \quad (3.7)$$

Other oil parameters are found likewise:

$$\begin{aligned} c_p &= 1.923 \text{ kJ}/(\text{kg} \cdot \text{K}), \lambda = 0.107 \text{ W}/(\text{m} \cdot \text{K}), \\ \text{Pr} &= 83.75, \beta \cdot = 7.11 \cdot 10^4 \text{ 1/K}; \nu = 5,47 \cdot 10^{-6} \text{ m}^2/\text{s}, \end{aligned} \quad (3.8)$$

where λ is heat conductivity,

Pr is Prandtl number,

β is volumetric thermal expansion coefficient,

ν is kinematic viscosity (momentum diffusivity).

Please note, that some values shown in the tables are multiplied by a power of ten. That is, for example, if $\nu \cdot 10^6 = 12 \text{ m}^2/\text{s}$, the actual value of it is $\nu = 12 \text{ m}^2/\text{s} \cdot 10^{-6} = 12 \cdot 10^{-6} \text{ m}^2/\text{s}$.

As the temperature of water in the present example fits a datum point in the table, interpolation of parameters for water is not needed, they could be just written out for this temperature:

$$\begin{aligned} \rho_{oH_2O} &= 999.7 \text{ kg/m}^3, \lambda_{H_2O} = 0.574 \text{ W}/(\text{m} \cdot \text{K}), \text{Pr}_{H_2O} = 9.52, \\ \beta_{H_2O} &= 1.65 \cdot 10^{-4} \text{ 1/K}, \nu_{H_2O} = 1.31 \cdot 10^{-6} \text{ m}^2/\text{s}, \mu_{H_2O} = 1.31 \cdot 10^{-3} \text{ Pa} \cdot \text{s}, \end{aligned} \quad (3.8)$$

where μ is dynamic viscosity.

The heat emission coefficient from oil to the tube wall is calculated according to the laws of heat transfer via forced convection for cases of fluid flow in pipes and channels. For this, firstly, the Reynolds number has to be found

$$\text{Re}_{\infty, d} = Wd_{\text{int}}/\nu = 1.2 \cdot 0.04/5,47 \cdot 10^{-6} = 8775.1. \quad (3.9)$$

Further solution depends on the Reynolds number value. There are three possible cases.

If $Re_{\infty,d} \leq 2300$, the heat emission coefficient has to be found according to the criterion equation for the viscous-gravitational heat transfer mode during laminar fluid flow

$$Nu_{\infty,d} = 0.15 Pe_{\infty,d}^{0,33} Ra_{\infty,d}^{0,1} \varepsilon_t \varepsilon_l, \quad (3.10)$$

where Peklet criterion is found with formula

$$Pe_{\infty,d} = Re_{\infty,d} \cdot Pr_{\infty}, \quad (3.11)$$

the Rayleigh number there

$$Ra_{\infty,d} = \frac{\beta g d_{int}^3 \vartheta_0}{\nu^2} Pr_{\infty} \quad (3.12)$$

includes unknown difference between temperatures of oil and tube surface

$$\vartheta_0 = \bar{t}_o - t_{int}. \quad (3.13)$$

Therefore, it is necessary to choose some temperature of the tube wall for performing the first approximation. Its value can be recommended to be set as

$$t_{int} = 0.5 \cdot (\bar{t}_o + t_w). \quad (3.15)$$

Equation (3.10) also includes deductions ε_l and ε_r that bring into account respectively the influence of the tube length and nonisothermality of boundary layer on the heat emission coefficient.

Because the length of the tube is unknown, set tentatively $\varepsilon_l = 1$.
 Nonisothermality deduction is

$$\varepsilon_T = (\text{Pr}_\infty / \text{Pr}_w)^{0,25}, \quad (3.16)$$

where Pr_w is Prandtl number for oil at temperature of the tube surface t_{int} found using the table A.5.

If $\text{Re}_{\infty,d} \geq 10^4$, the oil flow in the tube is turbulent. Then the heat emission coefficient from oil to the tube wall has to be found using the equation

$$\text{Nu}_{\infty,d} = 0,021 \text{Re}_{\infty,d}^{0,8} \text{Pr}_\infty^{0,43} \varepsilon_t \varepsilon_l, \quad (3.17)$$

where all the quantities included in the equation are the same as specified above.

In the case of $2300 < \text{Re}_{\infty,d} < 10^4$, the flow of oil in the tube is transient from laminar to turbulent. The heat emission coefficient for the transient flow can be determined as follows:

a) According to equation (3.10), the Nusselt number for the laminar flow mode is found at the value of the Peclet number $\text{Pe}_{\infty,d} = 2300 \cdot \text{Pr}_\infty$. Let's denote the found Nusselt number as Nu_l .

b) According to equation (3.17), the Nusselt number for the turbulent flow of oil is found for the value of the Reynolds number $\text{Re}_{\infty,d} = 10^4$. Let's denote the found Nusselt number as Nu_t .

c) The actual value of the Nusselt number is

$$\text{Nu}_{\infty,d} = \text{Nu}_l \left(\frac{\text{Re}_{\infty,d}}{2300} \right)^{1,47 \cdot \lg(\text{Nu}_t / \text{Nu}_l)}. \quad (3.18)$$

With Reynolds number found in (3.9) it is clear that it is transient flow takes place at conditions of present example. The order of solving for the case includes

calculations required for other two cases, and, if the data of the actual variant leads to laminar or turbulent flow, solving relying on this example should possible, but the formulas unnecessary for the case are to be omitted.

The order of calculation here, according to formulas (3.8) – (3.18), is as follows.

$$t_{int} = 0.5(62.5+10) = 36.25 \text{ }^{\circ}\text{C}. \quad (3.19)$$

$$g_0 = 62.5 - 36.25 = 26.25 \text{ K}. \quad (3.20)$$

$Pr_w = 167$ is interpolated from the table data for oil depending on t_{int} .

$$\varepsilon_t = (83.75/167)^{0.25} = 0.841. \quad (3.21)$$

$$Ra_{\infty,d} = \frac{7.11 \cdot 10^{-4} \cdot 9.81 \cdot 0.04^3 \cdot 26.25 \cdot 83.75}{(5.47 \cdot 10^{-6})^2} = 37.98 \cdot 10^6. \quad (3.22)$$

$$Pe_{t,d} = 2300 \cdot 83.75 = 192625. \quad (3.23)$$

$$Nu_t = 0.15 \cdot 192625^{0.33} \cdot 37982070^{0.1} \cdot 0.841 \cdot 1 = 40.09. \quad (3.24)$$

$$Nu_t = 0.021 \cdot 10000^{0.8} \cdot 83.75^{0.43} \cdot 0.501^{0.25} \cdot 1 = 188. \quad (3.25)$$

$$Nu_{\infty,d} = 40.09 \left(\frac{8775.1}{2300} \right)^{1.47 \cdot \lg(188/40.09)} = 150.2. \quad (3.26)$$

Because the definition of Nusselt number is

$$Nu_{\infty,d} = \alpha d / \lambda, \quad (3.27)$$

where λ here is heat conductivity of the oil at an mean oil temperature, the heat emission coefficient α_1 from oil to the tube surface can be found at determining size d equal d_{int} :

$$\alpha_1 = \text{Nu}_{\infty,d} \lambda / d_{\text{int}} = 150.2 \cdot 0.107 / 0.04 = 400.9 \text{ W/(m}\cdot\text{K)}. \quad (3.28)$$

Considering the thermal resistance of the tube wall, and the fact that the heat flow from oil to the tube is the same as through the wall, the temperature of the outer wall surfaces of the tube t_{out} can be found from

$$\alpha_1 d_{\text{int}} \vartheta_0 = 2\lambda_{\text{al}}(t_{\text{int}} - t_{\text{out}}) / \ln \frac{d_{\text{out}}}{d_{\text{int}}}, \quad (3.29)$$

$$400.9 \cdot 0.04 \cdot 26.25 = 2 \cdot 230(36.25 - t_{\text{out}}) / \ln \frac{0.042}{0.04},$$

$$t_{\text{out}} = 36.21 \text{ }^\circ\text{C}. \quad (3.30)$$

Through insignificant difference of the tube surfaces temperatures, this value can be safely accepted for equal to t_{int} in following calculations. But it is not necessarily true for all the variants.

Heat transfer on the outer surface of the tube can be found with a criterial equation of heat transfer via natural convection near horizontal cylinders:

$$\text{Nu}_{\infty,d H2O} = 0.5 \text{Ra}_{\infty,d H2O}^{0.25} \varepsilon_{t H2O}, \quad (3.31)$$

where Rayleigh number for the process is

$$\text{Ra}_{\infty,d H2O} = \frac{\beta_{H2O} g d_{\text{out}}^3 \vartheta_w}{\nu_{H2O}^2} \text{Pr}_{\infty H2O}, \quad (3.32)$$

where temperature difference for free convection is

$$\vartheta_w = t_{\text{out}} - t_w, \quad (3.33)$$

the nonisothermality deduction is

$$\varepsilon_{T_{H2O}} = (\text{Pr}_{\infty H2O} / \text{Pr}_{w H2O})^{0.25}, \quad (3.34)$$

Prandtl number $\text{Pr}_{w H2O}$ is found from the table A.6 for water parameters at t_{out} .

After calculating the Nusselt criterion in (3.31), the heat emission coefficient from the tube wall to the water is to be found

$$\alpha_2 = \text{Nu}_{\infty, d H2O} \lambda_{H2O} / d_{out}. \quad (3.35)$$

Calculating (3.31) – (3.35) in expedient order is as follows.

$$\vartheta_w = 36.21 - 10 = 26.21 \text{ K}. \quad (3.36)$$

$$\text{Ra}_{\infty, d} = \frac{1.65 \cdot 10^{-4} \cdot 9.81 \cdot 0.042^3 \cdot 26.21}{(1.31 \cdot 10^{-6})^2} \cdot 9.52 = 17.57 \cdot 10^6. \quad (3.37)$$

$\text{Pr}_w = 4.72$ is interpolated from the table data for water depending on t_{out} .

$$\varepsilon_t = (9.52/4.72)^{0.25} = 1.191. \quad (3.38)$$

$$\text{Nu}_{\infty, d} = 0.5 \cdot (17.57 \cdot 10^6)^{0.25} \cdot 1.191 = 38.57. \quad (3.39)$$

$$\alpha_2 = 38.57 \cdot 0.574 / 0.042 = 527.1. \quad (3.40)$$

When calculating the heat emission coefficient from oil to the tube, the tube inner surface temperature t_{int} was chosen voluntarily for the first approximation. The accuracy of setting this value needs to be checked, for which a balance of heat flows from oil to the tube wall and from the tube wall to water is set-up:

$$\alpha_1 \pi d_{int} (\bar{t}_o - t_{int}) = \alpha_2 \pi d_{out} (t_{out} - t_w). \quad (3.41)$$

If the difference in the heat balance exceeds 10%, then it is necessary to recalculate the temperatures of the tube surfaces. A new value of the wall temperature can be received by expressing t_{int} from (3.41). Then the calculations of the heat emission coefficients α_1 and α_2 have to be repeated.

The comparison of left and right parts of (3.41) shows error

$$\frac{400.9 \cdot 0.04(62.5 - 36.25) - 527.1 \cdot 0.042(36.21 - 10)}{400.9 \cdot 0.04(62.5 - 36.25)} = 38 \% > 10 \%, \quad (3.42)$$

meaning that t_{int} needs to be changed. Its new estimated value from (3.41) is

$$\begin{aligned} t_{int} &\approx t_{out} = (\bar{t}_o \alpha_1 d_{int} + \alpha_2 d_{out} t_w) / (\alpha_1 d_{int} + \alpha_2 d_{out}) = \\ &= (62.5 \cdot 400.9 \cdot 0.04 + 527.1 \cdot 0.042 \cdot 10) / (400.9 \cdot 0.04 + 527.1 \cdot 0.042) = 32.05^\circ\text{C}. \end{aligned} \quad (3.43)$$

All calculations (3.19)-(3.26), (3.28), (3.30), (3.35)-(3.40), (3.42) have to be repeated now with new values. Repeating of the calculations is not shown here, but must be present in the actual assignment solution.

It appears that value $t_{int} = 32.05^\circ\text{C}$ results in error 4.8% in (3.42). So, calculation can be continued after this second iteration with values of emission coefficients $\alpha_1 = 388.8 \text{ W}/(\text{m}\cdot\text{K})$, $\alpha_2 = 492.8 \text{ W}/(\text{m}\cdot\text{K})$ found from (3.28), (3.40).

The heat transfer coefficient k_l is found in accord to (3.6):

$$k_l = \frac{3.14}{\frac{1}{388.8 \cdot 0.04} + \frac{1}{492.8 \cdot 0.042} + \frac{1}{2 \cdot 230} \ln \frac{0.042}{0.04}} = 27.9 \text{ W}/(\text{m}\cdot\text{K}). \quad (3.44)$$

Lastly the tube length L is found using (3.2):

$$L = \frac{G_o c_{po} (t_1 - t_2)}{k_l (\bar{t}_o - t_w)} = \frac{1,289 \cdot 1923(65 - 60)}{27,9(62,5 - 10)} = 11.91 \text{ m}. \quad (3.45)$$

SELF-CHECK QUESTIONS FOR THE ASSIGNMENT 3

1. What are main modes of heat transfer?
2. The concept and types of uniqueness conditions.
3. What does Fourier hypothesis state?
4. The concept of free convection, the reasons for its occurrence.
5. The concept of forced convection, the reasons for its occurrence.
6. What similarity criteria are used to describe heat transfer phenomena?
7. What are thermal and hydrodynamic boundary layers?

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APPENDIX

Table A.1 – Heat capacities of carbon dioxide

| t , °C | μC_p , kJ/ (kmol K) | μC_v , kJ/ (kmol K) | μC_{pm} , kJ/ (kmol K) | μC_{vm} , kJ/ (kmol K) | C_{pm} , kJ/ (kg K) | C_{vm} , kJ/ (kg K) | C'_{pm} , kJ/ (m ³ K) | C'_{vm} , kJ/ (m ³ K) |
|-------------|--------------------------------|--------------------------------|-----------------------------------|-----------------------------------|-----------------------------|-----------------------------|--|--|
| 0 | 35.860 | 27.545 | 35.860 | 27.545 | 0.8148 | 0.6259 | 1.5998 | 1.2288 |
| 100 | 40.206 | 31.891 | 38.112 | 29.797 | 0.8658 | 0.6770 | 1.7003 | 1.3293 |
| 200 | 43.689 | 35.374 | 40.059 | 31.744 | 0.9102 | 0.7214 | 1.7373 | 1.4164 |
| 300 | 46.515 | 38.200 | 41.755 | 33.440 | 0.9487 | 0.7599 | 1.8027 | 1.4918 |
| 400 | 48.860 | 40.515 | 43.250 | 34.935 | 0.9826 | 0.7938 | 1.9207 | 1.5587 |
| 500 | 50.815 | 42.500 | 44.573 | 36.258 | 1.0128 | 0.8240 | 1.9837 | 1.6178 |
| 600 | 52.452 | 44.131 | 45.753 | 37.438 | 1.0396 | 0.8508 | 2.0411 | 1.6701 |
| 700 | 53.826 | 45.511 | 46.813 | 38.498 | 1.0639 | 0.8746 | 2.0884 | 1.7174 |
| 800 | 54.977 | 46.662 | 47.763 | 39.448 | 1.0852 | 0.8964 | 2.1311 | 1.7601 |
| 900 | 55.952 | 47.637 | 48.617 | 40.302 | 1.1045 | 0.9157 | 2.1692 | 1.7982 |
| 1000 | 56.773 | 48.458 | 49.392 | 41.077 | 1.1225 | 0.9332 | 2.2035 | 1.8326 |
| 1100 | 57.472 | 49.157 | 50.099 | 41.784 | 1.1384 | 0.9496 | 2.2349 | 1.8640 |
| 1200 | 58.071 | 49.756 | 50.746 | 42.425 | 1.1530 | 0.9638 | 2.2638 | 1.8929 |
| 1300 | 58.586 | 50.271 | 51.322 | 43.007 | 1.1660 | 0.9772 | 2.2898 | 1.9188 |
| 1400 | 59.030 | 50.715 | 51.858 | 43.543 | 1.1782 | 0.9893 | 2.3136 | 1.9427 |
| 1500 | 59.411 | 51.096 | 52.348 | 44.033 | 1.1895 | 1.0006 | 2.3354 | 1.9644 |
| 1600 | 59.737 | 51.422 | 52.800 | 44.485 | 1.1995 | 1.0107 | 2.3555 | 1.9845 |
| 1700 | 60.022 | 51.707 | 53.218 | 44.903 | 1.2091 | 1.0203 | 2.3743 | 2.0034 |
| 1800 | 60.269 | 51.954 | 53.604 | 45.289 | 1.2179 | 1.0291 | 2.3915 | 2.0205 |
| 1900 | 60.478 | 52.163 | 53.959 | 45.644 | 1.2259 | 1.0371 | 2.4074 | 2.0365 |
| 2000 | 60.654 | 52.339 | 54.290 | 45.975 | 1.2334 | 1.0446 | 2.4221 | 2.0511 |
| 2100 | 60.801 | 52.486 | 54.596 | 46.281 | 1.2405 | 1.0517 | 2.4359 | 2.0649 |
| 2200 | 60.918 | 52.603 | 54.881 | 46.566 | 1.2468 | 1.0580 | 2.4484 | 2.0775 |
| 2300 | 61.000 | 52.691 | 55.144 | 46.829 | 1.2531 | 1.0639 | 2.4602 | 2.0892 |
| 2400 | 61.060 | 52.745 | 55.391 | 47.076 | 1.2586 | 1.0697 | 2.4710 | 2.1001 |
| 2500 | 61.085 | 52.770 | 55.617 | 47.302 | 1.2636 | 1.0748 | 2.4811 | 2.1101 |

Table A.2 – Heat capacities of oxygen

| t , °C | μc_p , kJ/ (kmol K) | μc_v , kJ/ (kmol K) | μc_{pm} , kJ/ (kmol K) | μc_{vm} , kJ/ (kmol K) | c_{pm} , kJ/ (kg K) | c_{vm} , kJ/ (kg K) | c'_{pm} , kJ/ (m ³ K) | c'_{vm} , kJ/ (m ³ K) |
|-------------|--------------------------------|--------------------------------|-----------------------------------|-----------------------------------|-----------------------------|-----------------------------|--|--|
| 0 | 29.274 | 20.959 | 29.274 | 20.959 | 0.9148 | 0.6548 | 1.3059 | 0.9349 |
| 100 | 29.877 | 21.562 | 29.538 | 21.223 | 0.9232 | 0.6632 | 1.3176 | 0.9466 |
| 200 | 30.815 | 22.500 | 29.931 | 21.616 | 0.9353 | 0.6753 | 1.3352 | 0.9642 |
| 300 | 31.832 | 23.517 | 30.400 | 22.085 | 0.9500 | 0.6900 | 1.3561 | 0.9852 |
| 400 | 32.758 | 24.443 | 30.878 | 22.563 | 0.9651 | 0.7051 | 1.3775 | 1.0065 |
| 500 | 33.549 | 25.234 | 31.334 | 23.019 | 0.9793 | 0.7193 | 1.3980 | 1.0270 |
| 600 | 31.202 | 25.887 | 31.761 | 23.446 | 0.9927 | 0.7327 | 1.4168 | 1.0459 |
| 700 | 34.746 | 26.431 | 32.150 | 23.835 | 1.0018 | 0.7448 | 1.4344 | 1.0634 |
| 800 | 35.203 | 26.888 | 32.502 | 24.187 | 1.0157 | 0.7557 | 1.4499 | 1.0789 |
| 900 | 35.584 | 27.269 | 32.825 | 24.510 | 1.0258 | 0.7658 | 1.4645 | 1.0936 |
| 1000 | 35.914 | 27.599 | 33.118 | 24.803 | 1.0350 | 0.7750 | 1.4775 | 1.1066 |
| 1100 | 36.216 | 27.901 | 33.386 | 25.071 | 1.0434 | 0.7834 | 1.4892 | 1.1183 |
| 1200 | 36.488 | 28.173 | 33.633 | 25.318 | 1.0509 | 0.7913 | 1.5005 | 1.1296 |
| 1300 | 36.752 | 28.437 | 33.863 | 25.548 | 1.0580 | 0.7984 | 1.5106 | 1.1396 |
| 1400 | 36.999 | 28.684 | 34.076 | 25.761 | 1.0647 | 0.8051 | 1.5202 | 1.1493 |
| 1500 | 37.242 | 28.927 | 34.282 | 25.967 | 1.0714 | 0.8114 | 1.5294 | 1.1585 |
| 1600 | 37.480 | 29.165 | 34.474 | 26.159 | 1.0773 | 0.8173 | 1.5378 | 1.1669 |
| 1700 | 37.715 | 29.400 | 34.658 | 26.343 | 1.0831 | 0.8231 | 1.5462 | 1.1752 |
| 1800 | 37.945 | 29.630 | 34.834 | 26.519 | 1.0886 | 0.8286 | 1.5541 | 1.1832 |
| 1900 | 38.175 | 29.860 | 35.006 | 26.691 | 1.0940 | 0.8340 | 1.5617 | 1.1907 |
| 2000 | 38.406 | 30.091 | 35.169 | 26.854 | 1.0990 | 0.8390 | 1.5692 | 1.1978 |
| 2100 | 38.636 | 30.321 | 35.328 | 27.013 | 1.1041 | 0.8441 | 1.5759 | 1.2050 |
| 2200 | 39.858 | 30.543 | 35.483 | 27.168 | 1.1087 | 0.8491 | 1.5830 | 1.2121 |
| 2300 | 39.080 | 30.765 | 35.634 | 27.319 | 1.1137 | 0.8537 | 1.5897 | 1.2188 |
| 2400 | 39.293 | 30.978 | 35.785 | 27.470 | 1.1183 | 0.8583 | 1.5964 | 1.2255 |
| 2500 | 39.502 | 31.187 | 35.927 | 27.612 | 1.1229 | 0.8629 | 1.6027 | 1.2318 |
| 2600 | 39.708 | 31.393 | 36.069 | 27.754 | 1.1271 | 0.8675 | 1.6090 | 1.2380 |
| 2700 | 39.909 | 31.594 | 36.207 | 27.892 | 1.1313 | 0.8717 | 1.6153 | 1.2443 |

Table A.3 – Heat capacities of nitrogen

| t , °C | μc_p , kJ/ (kmol K) | μc_v , kJ/ (kmol K) | μc_{pm} , kJ/ (kmol K) | μc_{vm} , kJ/ (kmol K) | c_{pm} , kJ/ (kg K) | c_{vm} , kJ/ (kg K) | c'_{pm} , kJ/ (m ³ K) | c'_{vm} , kJ/ (m ³ K) |
|-------------|--------------------------------|--------------------------------|-----------------------------------|-----------------------------------|-----------------------------|-----------------------------|--|--|
| 0 | 29.115 | 20.800 | 29.115 | 20.800 | 1.0392 | 0.7423 | 1.2987 | 0.9278 |
| 100 | 29.199 | 20.884 | 29.144 | 20.829 | 1.0404 | 0.7427 | 1.3004 | 0.9295 |
| 200 | 29.471 | 21.156 | 29.228 | 20.913 | 1.0434 | 0.7465 | 1.3038 | 0.9328 |
| 300 | 29.952 | 21.657 | 29.383 | 21.068 | 1.0488 | 0.7519 | 1.3109 | 0.9399 |
| 400 | 30.576 | 22.261 | 29.601 | 21.286 | 1.0567 | 0.7599 | 1.3205 | 0.9496 |
| 500 | 31.250 | 22.935 | 29.864 | 21.549 | 1.0660 | 0.7691 | 1.3322 | 0.9613 |
| 600 | 31.920 | 23.605 | 30.149 | 21.834 | 1.0760 | 0.7792 | 1.3452 | 0.9743 |
| 700 | 32.540 | 24.225 | 30.451 | 22.136 | 1.0869 | 0.7900 | 1.3586 | 0.9877 |
| 800 | 33.101 | 24.786 | 30.748 | 22.433 | 1.0974 | 0.8005 | 1.3716 | 1.0006 |
| 900 | 33.599 | 25.284 | 31.037 | 22.722 | 1.1078 | 0.8110 | 1.3845 | 1.0136 |
| 1000 | 34.039 | 25.721 | 31.313 | 22.998 | 1.1179 | 0.8210 | 1.3971 | 1.0178 |
| 1100 | 34.424 | 26.109 | 31.577 | 23.262 | 1.1271 | 0.8302 | 1.4089 | 1.0379 |
| 1200 | 31.773 | 26.448 | 31.828 | 23.513 | 1.1359 | 0.8395 | 1.4202 | 1.0492 |
| 1300 | 35.070 | 26.745 | 32.067 | 23.752 | 1.1447 | 0.8478 | 1.4306 | 1.0597 |
| 1400 | 35.330 | 27.005 | 32.293 | 23.978 | 1.1526 | 0.8558 | 1.4407 | 1.0697 |
| 1500 | 35.556 | 27.231 | 32.502 | 24.187 | 1.1602 | 0.8633 | 1.4499 | 1.0789 |
| 1600 | 35.757 | 27.432 | 32.699 | 24.384 | 1.1673 | 0.8704 | 1.4587 | 1.0877 |
| 1700 | 35.937 | 27.612 | 32.883 | 24.568 | 1.1736 | 0.8771 | 1.4671 | 1.0961 |
| 1800 | 36.100 | 27.775 | 33.055 | 24.740 | 1.1798 | 0.8830 | 1.4746 | 1.1036 |
| 1900 | 36.247 | 27.922 | 33.218 | 24.903 | 1.1857 | 0.8889 | 1.4821 | 1.1112 |
| 2000 | 36.377 | 28.052 | 33.373 | 25.058 | 1.1911 | 0.8943 | 1.4888 | 1.1179 |
| 2100 | 36.494 | 28.169 | 33.520 | 25.205 | 1.1966 | 0.8997 | 1.1955 | 1.1246 |
| 2200 | 36.603 | 28.278 | 33.658 | 25.343 | 1.2012 | 0.9048 | 1.5018 | 1.1304 |
| 2300 | 36.703 | 28.378 | 33.787 | 25.472 | 1.2058 | 0.9094 | 1.5072 | 1.1363 |
| 2400 | 36.795 | 28.470 | 33.909 | 25.594 | 1.2104 | 0.9136 | 1.5127 | 1.1417 |
| 2500 | 36.879 | 28.554 | 34.022 | 25.707 | 1.2142 | 0.9177 | 1.5177 | 1.1468 |

Table A.4 – Heat capacities of steam

| t , °C | μc_p , kJ/ (kmol K) | μc_v , kJ/ (kmol K) | μc_{pm} , kJ/ (kmol K) | μc_{vm} , kJ/ (kmol K) | c_{pm} , kJ/ (kg K) | c_{vm} , kJ/ (kg K) | c'_{pm} , kJ/ (m ³ K) | c'_{vm} , kJ/ (m ³ K) |
|-------------|--------------------------------|--------------------------------|-----------------------------------|-----------------------------------|-----------------------------|-----------------------------|--|--|
| 0 | 33.499 | 25.184 | 33.499 | 25.184 | 1.8594 | 1.3980 | 1.4943 | 1.1237 |
| 100 | 34.055 | 25.740 | 33.741 | 25.426 | 1.8728 | 1.4114 | 1.5052 | 1.1342 |
| 200 | 34.964 | 26.649 | 34.118 | 25.803 | 1.8937 | 1.4323 | 1.5223 | 1.1514 |
| 300 | 36.036 | 27.721 | 34.575 | 26.260 | 19192 | 1.4574 | 1.5424 | 1.1715 |
| 400 | 37.191 | 28.876 | 35.090 | 26.775 | 1.9477 | 1.4863 | 1.5654 | 1.1945 |
| 500 | 38.406 | 30.091 | 35.630 | 27.315 | 1.9778 | 1.5160 | 1.5897 | 1.2188 |
| 600 | 39.662 | 31.347 | 36.195 | 27.880 | 2.0092 | 1.5474 | 1.6148 | 1.2439 |
| 700 | 40.951 | 32.636 | 36.789 | 28.474 | 2.0419 | 1.5805 | 1.6412 | 1.2703 |
| 800 | 42.249 | 33.934 | 37.392 | 29.077 | 2.0754 | 1.6140 | 1.6680 | 1.2971 |
| 900 | 43.513 | 35.198 | 38.008 | 29.693 | 2.1097 | 1.6483 | 1.6957 | 1.3247 |
| 1000 | 44.723 | 36.408 | 38.619 | 30.304 | 2.1436 | 1.6823 | 1.7229 | 1.3519 |
| 1100 | 45.858 | 37.513 | 39.226 | 30.911 | 2.1771 | 1.7158 | 1.7501 | 1.3791 |
| 1200 | 46.913 | 38.598 | 39.825 | 31.510 | 2.2106 | 1.7488 | 1.7769 | 1.4059 |
| 1300 | 47.897 | 39.582 | 40.407 | 32.092 | 2.2429 | 1.7815 | 1.8028 | 1.4319 |
| 1400 | 48.801 | 40.486 | 40.976 | 32.661 | 2.2743 | 1.8129 | 1.8280 | 1.4570 |
| 1500 | 49.639 | 41.324 | 41.525 | 33.210 | 2.3048 | 1.8434 | 1.8527 | 1.4817 |
| 1600 | 50.409 | 42.094 | 42.056 | 33.741 | 2.3346 | 1.8728 | 1.8761 | 1.5052 |
| 1700 | 51.133 | 42.818 | 42.576 | 34.261 | 2.3630 | 1.9016 | 1.8996 | 1.5286 |
| 1800 | 51.782 | 43.467 | 43.070 | 34.755 | 4.3907 | 1.9293 | 1.9213 | 1.5504 |
| 1900 | 52.377 | 44.062 | 43.539 | 35.224 | 2.4166 | 1.9552 | 1.9423 | 1.5713 |
| 2000 | 52.930 | 44.615 | 43.995 | 35.680 | 2.4422 | 1.9804 | 1.9628 | 1.5918 |
| 2100 | 53.449 | 45.134 | 44.435 | 36.120 | 2.4664 | 2.0051 | 1.9824 | 1.6115 |
| 2200 | 53.930 | 45.615 | 44.853 | 36.538 | 2.4895 | 2.0281 | 2.0009 | 1.6299 |
| 2300 | 51.370 | 46.055 | 45.255 | 36.940 | 2.5 121 | 2.0503 | 2.0189 | 1.6479 |
| 2400 | 54.780 | 46.465 | 45.644 | 37.330 | 2.5334 | 2.0720 | 2.0365 | 1.6655 |
| 2500 | 55.161 | 46.846 | 46.017 | 37.702 | 2.5544 | 2.0926 | 2.0528 | 1.6818 |
| 2600 | 55.525 | 47.210 | 46.381 | 38.066 | 2.5745 | 2.1131 | 2.0691 | 1.6982 |
| 2700 | 55.864 | 47.549 | 47.729 | 38.414 | 2.5937 | 2.1323 | 2.0864 | 1.7137 |

Table A.5 – Thermophysical properties of transformer oil

| t , °C | c_p , kJ/(kg·K) | $\nu \cdot 10^6$, m ² /s | Pr | ρ , kg/m ³ | $\lambda \cdot 10^2$, W/(m·K) | $\beta \cdot 10^4$, 1/K |
|-------------|----------------------|---|-----|-------------------------------|-----------------------------------|--------------------------|
| 10 | 1.67 | 22.50 | 298 | 880 | 11.1 | 6.90 |
| 20 | 1.67 | 22.50 | 298 | 880 | 11.1 | 6.90 |
| 30 | 1.73 | 14.70 | 202 | 874 | 11.0 | 6.95 |
| 40 | 1.79 | 10.30 | 146 | 868 | 10.9 | 7.00 |
| 50 | 1.85 | 7.58 | 111 | 862 | 10.8 | 7.05 |
| 60 | 1.91 | 5.78 | 88 | 856 | 10.7 | 7.10 |
| 70 | 1.96 | 4.54 | 71 | 850 | 10.6 | 7.15 |
| 80 | 2.03 | 3.66 | 59 | 844 | 10.6 | 7.20 |
| 90 | 2.09 | 3.03 | 51 | 838 | 10.5 | 7.25 |

Table A.6 – Thermophysical properties of water

| t , °C | c_p , kJ/(kg·K) | $\nu \cdot 10^6$, m ² /s | Pr | ρ , kg/m ³ | $\lambda \cdot 10^2$, W/(m·K) | $\beta \cdot 10^4$, 1/K | $\mu \cdot 10^6$, Pa·s |
|----------|----------------------|---|-------|-------------------------------|-----------------------------------|-----------------------------|----------------------------|
| 0 | 4.212 | 1.789 | 13.67 | 999.9 | 55.1 | 0.99 | 1 666.7 |
| 10 | 4.191 | 1.306 | 9.52 | 999.7 | 57.4 | 1.65 | 1 306.0 |
| 20 | 4.183 | 1.006 | 7.02 | 998.2 | 59.9 | 1.82 | 1 004.0 |
| 30 | 4.174 | 0.805 | 5.42 | 995.7 | 61.8 | 3.21 | 801.5 |
| 40 | 4.174 | 0.659 | 4.31 | 992.2 | 63.5 | 3.87 | 653.3 |
| 50 | 4.174 | 0.556 | 3.54 | 988.1 | 64.8 | 4.49 | 549.4 |
| 60 | 4.179 | 0.478 | 2.98 | 983.2 | 65.9 | 5.11 | 469.9 |
| 70 | 4.187 | 0.415 | 2.55 | 977.8 | 66.8 | 5.70 | 406.1 |
| 80 | 4.195 | 0.365 | 2.21 | 971.8 | 67.4 | 6.32 | 355.1 |
| 90 | 4.208 | 0.326 | 1.95 | 965.3 | 68.0 | 6.95 | 314.9 |
| 100 | 4.220 | 0.295 | 1.75 | 958.4 | 68.3 | 7.52 | 282.5 |

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Навчальне видання

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з дисципліни «Теоретичні основи теплотехніки»

Укладач ПИЛЬОВ Вячеслав Володимирович

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