HEAT EXCHANGE IN STEAM GENERATOR WITH LOW BOILING POINT FLUID

by

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The heat transfer processes in the main zones of the steam generator of low temperature power plant are considered. An experimentally substantiated method of taking into account the tube wall effect during nucleate boiling in case of a two-phase flow of case of a working fluid inside the tube is implemented by mathematical modelling. The heat exchange characteristics are presented for each of the zones of steam generator with low boiling point fluid R245fa.

Key words: *Rankine cycle, recuperation, in-line boiling, wall effect, thermal similarity criteria, pipe roughness*

Introduction

One of the directions of the energy strategy in the world is the wider involvement of unused and newly created alternative energy sources in economic activity. As a rule, these are heat sources with low (conditionally) temperature $t \leq 130$ °C. Standard solutions in steam-water heating equipment for the use of such heat sources are known: these are heat, cold, and electricity supplies. Further development of these energy-saving areas is on the way of increasing the thermal and economic efficiency of technologies (heat pump, their combinations with traditional heat sources in the form of bivalent installations; geothermal, binary and solar power plants, wind turbines). Despite the relatively low density of available energy of thermal sources, the improvement of ecology and social effects should be considered in favor of their development. There is an opportunity to increase the efficiency of existing conventional installations and to achieve their competitiveness in comparison with other energy sources because of a decrease in operating costs due to the absence (full or partial) of the fuel component and an increase in prices of fossil fuel [1-11].

Special attention should be paid to the creation of renewable sources of thermal energy on dry hot rocks of the Earth [12], not associated with volcanic activity, for later converting into electricity, as a universal form of energy, at the place of consumption and heat for heat supply systems (cogeneration). However, effective conversion of low potential thermal energy into electrical energy (and thermal energy of a higher potential) requires the creation of special thermal-mechanical equipment. Research, development and construction of low potential energy-saving technological equipment for diversified purposes should be considered as a promising technical groundwork for the development of heat power engineering.

The purpose of the presented work was to determine the heat exchange characteristics of the main zones of the steam generator when taking the required amount of heat from the

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geothermal source with subsequent substantiation of technical specifications for the design of equipment. To carry out optimization feasibility studies, a generalized mathematical model of a low temperature unit, developed in previous works of the authors, was applied.

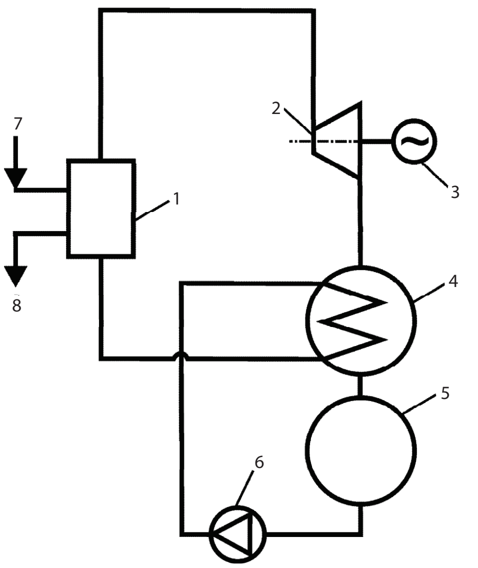

Figure 1. A schematic diagram of a steam power cycle with waste heat recovery;
1 – steam generator, 2 – turbine, 3 – generator, 4 – recuperator, 5 – condenser, 6 – pump, 7 – inlet of heating low potential heat carrier, and 8 – outlet to the heat supply system

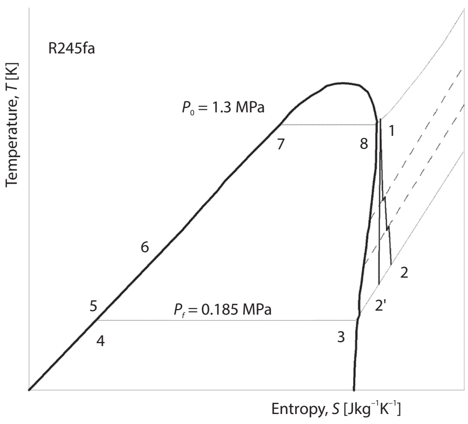

Figure 2. Organic Rankine cycle in T-S diagram for pentafluoropropane (R245fa);
1-2 – steam expansion in the turbine,
2-3 – heat removal in the recuperator,
3-4 – heat removal in the condenser,
4-5 – pressure increase in the feed pump,
6-7 – heat supply from external heat source

Problem statement

The task of mathematical modelling of thermal processes of a steam generator is to find out heat exchange characteristics that determine its structural heating surfaces, affecting the technological profile of a power plant for technical design. A schematic diagram of a steam power cycle with waste heat recovery is shown in fig. 1.

Due to the heat of the heating source in the steam generator – 1, heating, boiling, and overheating of the working fluid take place. In this work, R245fa is considered as a working fluid for a low temperature power plant with a capacity of 3000 kW, used to generate electricity from thermal energy resources of low potential. Thermophysical properties of R245fa are taken in accordance with [13, 14]. The temperature range of effective use of R245fa as a working fluid in the organic ORC is 80-150 °C. The indicated temperature range follows from the analysis of the Rankine cycle, presented in [15]. Thermodynamic cycle for the circuit shown in fig. 1 represents the organic Rankine cycle, which is shown in fig. 2 as a *TS* diagram. The initial data with substantiation of the initial steam pressure in front of the turbine P_0 and the final P_f at the nodal points of the presented cycle are given in [15]. Taking into account the loss of steam pressure in the control valves of the turbine (5%), the pressure of the working fluid behind the feed pump is calculated as 13.7 bar (not considering the pressure loss along the path of movement), which is necessary to determine its thermophysical properties.

It is assumed that the high pressure coolant moves inside the pipes, while the low pressure coolant is located in the inter-tube space.

For the mathematical description of heat transfer processes in the steam generator, experimentally substantiated equations were written in dimensionless form using similarity criteria.

Research block diagram

The block diagram of the research algorithm for the energy and feasibility study of using thermal energy for electricity and heat supply to consumers is shown in fig. 3 [16]. Here, the block of control and optimization contains the necessary initial information on arrangement of installations, their operating conditions, and range of parameters that characterize the series of options under consideration. From the first block, we turn to calculation of the technological scheme of the installation. Block 2 can be conventionally represented as consisting of three parts. The first of them is intended to describe the processes that determine the parameters of the working bodies used in the installation. The second part describes the processes of energy transformation and transmission in individual elements of installation, including turbine generator and heat exchangers. This takes into account all the main physical processes associated with the use of working fluid. The third part simulates a real technological scheme of the considered technologies. Thus, the initial data required for the design calculations of the equipment are formed (Block 3). In Block 4, the technical and economic indicators for equipment and installation as a whole are calculated, taking into account external influencing relations. The memory block (Block 5) records the values of parameters and characteristics of the installation, calculated in the previous Blocks 2-4, in order to use them in further calculations or in printing. In this case, direct and feedback connections between Blocks 1 and 5 are implemented, which allows the control and optimization unit to call the necessary numerical values of quantities and information on the performance of the next operation from the memory block, check logical conditions and send the result to Block 5. Thus, the computational process is controlled according to the calculation algorithm.

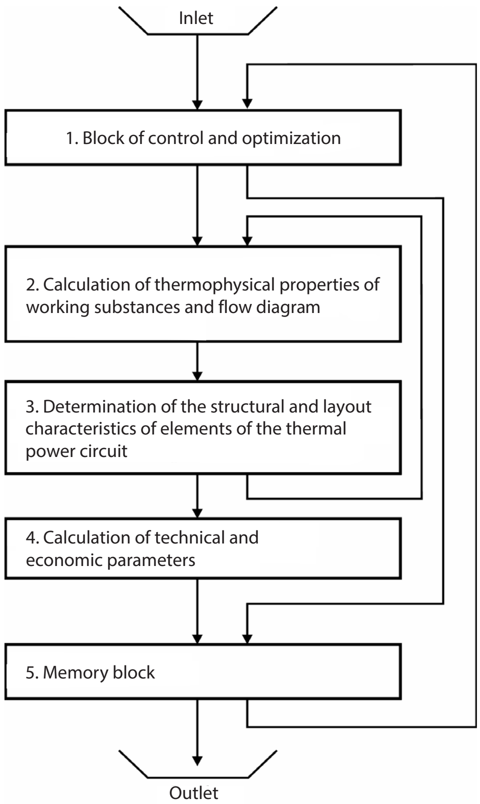

Figure 3. Structural block diagram of the research algorithm

Solution method

In mathematical modelling of the steam generator with working fluid shown in fig. 1, the following heat exchange zones are considered: zones of heating, boiling, and superheating. A feature of using R245fa as a working fluid, which is promising for low temperature power plants, is a high steam temperature at the end of the expansion process [15], and it becomes necessary to return (recuperate) part of the residual heat into the steam-power cycle. The latter allows determination of the initial parameters of the working fluid in the economizer zone of steam generator from an external heat source (point 6 in fig. 2). The heating medium is a water heat carrier with a temperature of 140 °C in countercurrent with the working fluid. Thermal loads at boiling and superheating of R245fa make it possible to determine the flow rate of the heating medium when setting the temperature difference between the heat exchanging media.

The convective heat transfer coefficient during the in-line movement of a single-phase flow (heating and overheating of the working fluid) is determined by the dependence [17] with subsequent correlations [18, 19]:

$$\mathrm{Nu} = \frac{\left(\dfrac{f}{8}\right)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7\left(\dfrac{f}{8}\right)^{1/2}\left(\mathrm{Pr}^{2/3}-1\right)} \tag{1}$$

The aforementioned dependence is valid for $2.3\cdot10^3 < \mathrm{Re} < 10^6$, $0.6 < \mathrm{Pr} < 2000$. Here $\mathrm{Nu} = \alpha d/\lambda$, $\mathrm{Re} = ud/\nu$, $\mathrm{Pr} = \mu c_p/\lambda$ are generally accepted similarity criteria of Nusselt, Reynolds, and Prandtl numbers, respectively, α [Wm^{-2}K^{-1}] is the heat transfer coefficient, d [m] – the inner tube diameter, u [ms^{-1}] – the flow velocity, c_p, λ, ν, and μ are isobaric heat [kJkg^{-1}K^{-1}], heat conductivity [Wm^{-1}K^{-1}], kinematic viscosity, [m^{2}s^{-1}], and dynamic viscosity, [Pa·s], respectively; f is friction resistance coefficient for turbulent flow of liquid:

$$f = \frac{1}{\left(1.82\,\mathrm{lgRe}-1.64\right)^2} \tag{2}$$

The thermophysical properties of the working fluids were taken according to their average temperature in the calculated area.

To calculate the heat transfer coefficient of a single-phase medium in-between the tubes at $10 < \mathrm{Re} < 10^7$, the dependence [18-20] is used:

The thermophysical properties of the working fluids were taken according to their average temperature in the calculated area.

$$\mathrm{Nu}_{0,\mathrm{bank}} = f_\mathrm{A}\left[0.3+\left(\mathrm{Nu}_{\mathrm{L,l}}^2+\mathrm{Nu}_{\mathrm{L,t}}^2\right)^{0.5}\right] \tag{3}$$

where f_A is the structural factor of the tube bundle:

$$\mathrm{Nu}_{\mathrm{L,l}} = 0.664\mathrm{Re}_{\psi,\mathrm{L}}{}^{1/2}\,\mathrm{Pr}^{1/3} \tag{4}$$

$$\mathrm{Nu}_{\mathrm{L,t}} = \frac{0.037\,\mathrm{Re}_{\psi,\mathrm{L}}{}^{0.8}\,\mathrm{Pr}}{1+2.443\,\mathrm{Re}_{\psi,\mathrm{L}}{}^{-0.1}\,(\mathrm{Pr}^{2/3}-1)} \tag{5}$$

These relationships are valid in the following range of similarity criteria $10 < \mathrm{Re}_{\psi,\mathrm{L}} < 10^5$, $0.6 < \mathrm{Pr} < 10^3$. Here:

$$\mathrm{Re}_{\psi,\mathrm{L}} = \frac{uL}{\psi\nu} \tag{6}$$

where $\psi = 1 - \pi/4a$ is the proportion of voids not occupied by the cylinder, a – the relative transverse step of tubes in a bundle with their staggered arrangement, w/ψ – the average velocity in a gap between two adjacent tubes, L – the length of the flow around a single tube. Calculation of the process of steam heat recovery after the turbine allows determination of the initial parameters of the working fluid for heating it from an external heating source and parameters of steam entering the condensing device of the power plant. Subcooling of condensate in front of the condensate feed pump is accepted to be 3 °C.

Table 1 shows the heat transfer characteristics of the recuperation process of steam heat at the turbine outlet to the recuperator (economizer zone of the steam generator) for heating working fluid after condensation.

Table 1. Cycle parameters and heat transfer characteristics of the recuperator

Steam pressure behind the turbine [bar]		1.85
Steam temperature behind the turbine [°C]		59
Condensation temperature, [°C]		30.9
Working fluid velocity [ms^{-1}]		1.2
Temperature of R245fa vapor at recuperator outlet [°C]		43.0
Average steam velocity in-between the tubes [ms^{-1}]		1.75
Heat loads, Q [kW]	Recuperator	2118
	Steam generator	29540
Similarity criteria (in-line flow)	Pr	5.71
	Re	72880
	Nu	417

Table 2 shows the results of determining the heat transfer characteristics of the heating process of R245fa refrigerant in the steam generator of the power plant. To calculate the heat exchange surface of the boiling zone of a working fluid, it is necessary to know the numerical values of the average heat transfer coefficient in the dryness range from 0 to 1.0. In the case of working fluid boiling in tubes, the intensity of heat transfer is caused by combination of boiling processes and forced movement of a two-phase medium. The analysis of physical processes and parametric studies during boiling of working bodies were considered in [21-33]. Currently, there are a number of calculation methods for determining the heat transfer coefficient during boiling of liquid in traditional channels [21, 22, 28, 29, 31]. The presented dependences summarize the experimental data on boiling of some substances within ± 20%. The choice of the calculation method for determining the heat transfer coefficient was based on experimental data on boiling of fluids, taking into account the effect of not only the thermophysical properties of liquid, but also the dividing wall supplying heat from the heating source. Table 3 shows the thermophysical properties of R245fa in the boiling zone.

Table 2. Heat transfer characteristics in the R245fa heating section

P = 13.7 bar, t_{av} = 71.9 °C		P = 1.2 bar, t_{av} = 104.9 °C	
Re	156700	$Re_{\psi,L}$	33240
Pr	4.49	Pr	1.68
u [ms^{-1}]	1.2	w/ψ	0.3
Nu	720	$Nu_{0,bank}$	720

Table 3. Thermophysical properties of R245fa in boiling zone (P = 1.7 bar, t = 103.77 °C)

Name	Liquid phase	Vapor phase	Water
Density, ρ [kgm^{-3}]	1077.0	78.850	954.5
Heat capacity, c_p [$kJkg^{-1}K^{-1}$]	1.629	1.287	4.2
Dynamic viscosity, μ [Pa·s]	$1.57\cdot10^{-4}$	$1.36\cdot10^{-5}$	$2.71\cdot10^{-4}$
Kinematic viscosity, ν [m^2s^{-1}]	$1.46\cdot10^{-7}$	$1.72\cdot10^{-7}$	$2.83\cdot10^{-7}$
Heat conductivity, λ [$Wm^{-1}K^{-1}$]	0.0663	0.0220	0.684
Surface tension, σ [Nm^{-1}]	0.00436		0.0579
Heat load in boiling zone, Q [kW]	16900		

During mathematical modelling of the zone of R245fa boiling in a steam generator, heat transfer during nucleate boiling with forced motion of a two-phase medium is considered. The results of generalization of a large array of experimental data on heat transfer during boiling of various fluids in a wide range of pressure and heat fluxes, including low boiling substances, using the results of the author [29] and other authors [21-23, 31] are presented in [29]. These data refer to thick-walled tubes made of different metals with different roughness and they are satisfactorily described by the empirical dependence, which takes into account the effect of wall through its thermophysical properties:

$$\mathrm{Nu}^* = 0.01\mathrm{Re}_*^{0.8}\mathrm{Pr}^{1/3} b K_t^{0.4}\, \overline{R}_z^{0.2}\left(\frac{\lambda' c_p' \rho'}{\lambda_\mathrm{w} c_\mathrm{w} \rho_\mathrm{w}}\right)^{-0.2} \tag{7}$$

where $\mathrm{Nu}^* = \alpha l_\sigma/\lambda$ is modified Nusselt number, where $l_\sigma = [\sigma/\mathrm{g}(\rho' - \rho'')]^{0.5}$ [m] – the capillary constant of liquid, $\mathrm{Re}_* = q l_\sigma / r\rho''\nu$ – the Reynolds number at boiling, calculated by evaporation rate, where q [Wm^{-2}] – specific heat flux, r [Jkg^{-1}] – latent heat of vaporization, ν [m^{2}s^{-1}] – kinematic viscosity of liquid, ρ', ρ'' [kgm^{-3}] are specific densities of liquid and vapor phases, respectively, g [ms^{-2}] – acceleration of gravity, σ [Nm^{-1}] – surface tension coefficient, and α [Wm^{-2}K^{-1}] – heat transfer coefficient

$$b = 1 + 10\left(\frac{\rho''}{\rho' - \rho''}\right)^{2/3}$$

is dimensionless complex, and K_t is criterion of heat similarity:

$$K_\mathrm{t} = \frac{(r\rho'')^2\, l_\sigma}{c_p T_\mathrm{s}\, \rho'\sigma} \tag{8}$$

where T_s [K] is saturation temperature

$$\overline{R}_z = \frac{R_z}{\left(\dfrac{u^2}{\mathrm{g}}\right)^{1/3}}$$

is dimensionless roughness, R_z is characteristic size of roughness, and

$$\left(\frac{\lambda' c_p' \rho'}{\lambda_\mathrm{w} c_\mathrm{w} \rho_\mathrm{w}}\right)$$

is ratio of physical properties of liquid to physical parameters of the wall.

It was found out [21] that at a large heat flux, the ratio of the heat transfer coefficients during boiling of liquid in a tube and at pool boiling tends to unity, which indicates the correctness of using dependence eq. (8) when working fluid boiling under conditions of forced convection in tubes.

To calculate the average heat transfer coefficient α during boiling of working fluid moving in tubes, the dependence [21], which is in good agreement with experiment, is used:

$$\alpha = \alpha_\mathrm{k}\left[1 + \left(\frac{\alpha_0}{\alpha_\mathrm{k}}\right)^2\right]^{0.5} \tag{9}$$

where α_k [Wm^{-2}K^{-1}] is convective component of the heat transfer coefficient without boiling eq. (1) and α_0 [Wm^{-2}K^{-1}] – the heat transfer coefficient at developed nucleate boiling.

In the process of transferring heat energy from the primary coolant to boiling R245fa, it is required to comply with the adopted nucleate boiling regime, as the most effective, in which the value of specific heat flux, q, is less than the first critical heat flux, q_{cr1}, determined by the equation [21]:

$$q_{\mathrm{cr1}} = kr\left(\rho''\right)^{1/2}[\mathrm{g}\sigma\left(\rho'-\rho''\right)]^{1/4} \tag{10}$$

where k is criterion of two-phase flow stability, whose numerical value, in accordance with [21], is taken to be 0.14.

Setting the specific heat flux in the boiling zone is associated with organization of an iterative process that satisfies:

$$q = \alpha_1\left(t_1 - t_{\mathrm{w}1}\right) \tag{11}$$

$$q = \frac{\lambda_{\mathrm{w}}}{\delta}\left(t_{\mathrm{w}1} - t_{\mathrm{w}2}\right) \tag{12}$$

$$q = \alpha_2\left(t_{\mathrm{w}2} - t_2\right) \tag{13}$$

$$q = K\Delta\overline{T} \tag{14}$$

$$K = \frac{1}{\dfrac{1}{\alpha_1}\dfrac{D}{d} + \dfrac{D}{2\lambda_{\mathrm{w}}}\ln\dfrac{D}{d} + \dfrac{1}{\alpha_2}} \tag{15}$$

where t_1, t_2 [°C] are the temperatures of heat source and boiling liquid, D and d [m] – the outer and inner diameters of tube, $t_{\mathrm{w}1}$ and $t_{\mathrm{w}2}$ [°C] – the wall temperatures from the side of heating medium and boiling liquid, δ [m] – the thickness of heat exchanging wall, λ_{w} [Wm^{-1}K^{-1}] – the coefficient of metal heat conductivity, α_1 and α_2 [Wm^{-2}K^{-1}] are the heat transfer coefficients for the heating medium and boiling liquid, K – the heat transfer coefficient, $\Delta\overline{T}$ – the mean logarithmic temperature head. The basis for implementation of these methodological provisions is the knowledge of the specific heat flux q required to determine the Reynolds number during boiling of a working fluid. The value $q_0 = q_{\mathrm{cr1}}/10$, at which accepted nucleate regime of boiling is observed, was taken as an initial approximation. This allows determination of the heat transfer coefficient, K, in the boiling zone and calculated specific heat flux q_i. At $q_i \neq q_0$, an iterative process is organized, which allows matching the heat flux and heat exchange characteristics with a given error.

Table 4. Heat exchange characteristics at boiling R245fa in steam generator

Parameters			
l_σ [m]	$6.68\cdot10^{-4}$	Nu^*	49.1
Pr	3.85	α_0 [Wm^{-2}K–1]	4880
K_t	$24.9\cdot10^3$	α_{k} [Wm^{-2}K^{-1}]	2370
R_z [μm]	0.2	α [Wm^{-2}K^{-1}]	5420
$\overline{R}_z^{\,0.2}$	0.605	$\Delta\overline{T}$ [K]	19.7
$\left(\dfrac{\lambda' c'_p\rho'}{\lambda_{\mathrm{w}}c_{\mathrm{w}}\rho_{\mathrm{w}}}\right)^{-0.2}$	4.52	q_{cr1} [Wm^{-2}]	$419\cdot10^3$

Table 4 shows the results of calculations of heat transfer characteristics during boiling of R245fa. Overheating of working fluid by 3 °C is accepted to compensate a decrease in the temperature of dry saturated steam during its adiabatic throttling in the turbine control valves (for the considered parameters of R245fa, the Joule-Thomson effect is 1.84 K/bar).

In the mathematical modelling of the in-line boiling process, the methodological provisions of [30] are implemented. When analyzing the results presented in tab. 4, two parameters attract attention: dimensionless roughness of the traditional tube surfaces of shell-and-tube heat exchangers and the influence of thermophysical properties of the heat exchange wall. Parameter

$$\bar{R}_z^{0.2} = 0.605 < 1$$

and in accordance with [30], it follows that the relative roughness $\bar{R}_z$ does not affect heat transfer during boiling of R245fa. The total effect of the heat transfer wall, with consideration of its thermophysical properties, parameter:

$$\left[\frac{\lambda' c_p' \rho'}{\lambda_\mathrm{w} c_\mathrm{w} \rho_\mathrm{w}}\right]^{-0.2} = 4.517$$

is estimated as an increase in the Nusselt number during R245fa boiling by

$$\bar{R}_z^{0.2}\left[\frac{\lambda' c_p' \rho'}{\lambda_\mathrm{w} c_\mathrm{w} \rho_\mathrm{w}}\right]^{-0.2} = 2.73$$

Conclusions

- A mathematical model of steam generator with a low boiling point fluid for generating electricity when using low temperature energy resources has been developed. Residual heat after a turbine is recuperated to heat the working fluid. The heat exchange characteristics of the recuperator and steam generator have been determined at the example of using R245fa as one of the promising working substances of such installations.
- The recuperator can reduce the heat load on the steam generator with R245fa by 6.9%.
- The boiling zone accounts for 57.4% of steam generator heat output. With in-tube boiling of R245fa, the contribution of the heat transfer wall is an increase in the heat transfer coefficient by 5.6%.

Nomenclature

a – relative transverse step of tubes
b – dimensionless complex, [–]
c_p – heat capacity, [kJkg^{-1}K^{-1}]
D – outer tube diameter, [m]
d – inner tube diameter, [m]
f – friction resistance, [–]
f_A – structural factor of the tube bundle, [–]
g – acceleration gravity, [ms^{-2}]
K – heat transfer coefficient, (Wm^{-2}K^{-1})
L – length of the flow around a single tube, [m]
l – capillary constant of liquid, [m]
Nu – Nusselt number, [–]
Pr – Prandtl number, [–]
Q – heat load in boiling zone, [kW]
q – specific heat flux, [Wm^{-2}]
Re – Reynolds number (= uD/ν), [–]
R_z – roughness, [μm]
r – latent heat vaporization, [Jkg^{-1}]
$\Delta\bar{T}$ – mean logarithmic temperature head, [°C]
t – temperature, [°C]
u – flow velocity, [ms^{-1}]

Greek letter

α – heat transfer coefficient, [Wm^{-2}K^{-1}]
δ – wall thickness, [m]
λ – heat conductivity, [Wm^{-1}K^{-1}]
μ – dynamic viscosity, [Pa·s]
ν – kinematic viscosity, [m^{2}s^{-1}]
ρ – density, [kgm^{-3}]
σ – surface tension, [Nm^{-1}]
ψ – proportion of voids not occupied by the cylinder

Subscripts/superscripts

′ – liquid phase
w – wall
″ – vapor phases
$_*$ – boiling point test
* – modified criterion
cr1 – first critical
k – convective
L, l – laminar boundary-layer
L, t – turbulent boundary-layer
o, bank – single-phase medium in-between the tubes
p – pressure
s – saturation
t – criterion of heat similarity

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