Энергетика. Изв. высш. учеб. заведений и энерг. объединений СНГ. Т. 63, № 1 (2020), с. 81–88
Energetika. Proc. CIS Higher Educ. Inst. and Power Eng. Assoc. V. 63, No 1 (2020), pp. 81–88

https://doi.org/10.21122/1029-7448-2020-63-1-81-88

UDC 536.24

Calculation of Heat Exchange on the Surface of a Flexible Heat Exchanger for Use in Mobile Hospitals

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Abstract. Currently, the world is characterized by quite a large number of military conflicts, man-made disasters and natural disasters. Every year, about 50 thousand people die from various natural disasters in the world. The report of the UNISDR notes that natural disasters that occurred in the world between 1998 and 2017 led to the death of 1.3 million people (more than half of them – due to earthquakes). The analysis shows that human losses could be significantly less with rapid first aid. This requires the presence of a field hospital located as close as possible to the lesion. Currently, field hospitals for various purposes are produced. The heating system of the field hospital modules plays an important role in the operation. A heating system is proposed, which includes a vortex heat generator and heating devices made of polyvinyl chloride. The system is characterized by low weight and quick access to the operating mode. However, in the literature there is no method for calculating the heat exchange coefficient in a closed space, which is formed by flexible heater surface and an enclosing wall. Based on the analysis of criterion dependences and experimental data, new criterion equations for calculating the heat exchange coefficient for an arbitrary location of heaters in space are obtained. The following dependence is built $\lg\mathrm{Nu} = f(\lg(\mathrm{Gr}\cdot\mathrm{Pr}))$, which allows to determine value of heat exchange coefficient for given range of temperature. A method of intensification of the heat exchange process by creating an artificial roughness is proposed. Graph is done to determine growth rate of heat exchange C_K, which is included in criterion equation. The use of artificial roughness allowed increasing the heat transfer coefficient by 28 % and the thermal power of the heating device by about 26 %.

Keywords: field hospital, heat supply system, heat transfer coefficient, criterion equation, intensification

For citation: Iokova I. L., Kalinichenko A. S. (2020) Calculation of Heat Exchange on the Surface of a Flexible Heat Exchanger for Use in Mobile Hospitals. *Energetika. Proc. CIS Higher Educ. Inst. and Power Eng. Assoc.* 63 (1), 81–88. https://doi.org/10.21122/1029-7448-2020-63-1-81-88

Расчет теплообмена на поверхности гибкого теплообменника для применения в мобильных госпиталях

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Реферат. Сегодня мир характеризуется достаточно большим количеством военных конфликтов, техногенных катастроф, стихийных бедствий. Ежегодно от разного рода природных катаклизмов на планете погибает около 50 тыс. человек. В докладе Управления ООН по уменьшению опасности стихийных бедствий (ЮНИСДР) отмечается, что стихийные бедствия,

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которые произошли в мире за период с 1998 по 2017 г., привели к гибели 1,3 миллиона человек (свыше половины из них – из-за землетрясений). Анализ показывает, что людские потери могли бы быть значительно меньше при быстром оказании первой медицинской помощи. Это требует наличия госпиталя, расположенного как можно ближе к очагу поражения. В настоящее время создаются полевые госпитали различного назначения. Важную роль в их функционировании играет система обогрева модулей. Предложена система отопления, которая включает в себя вихревой теплогенератор и нагревательные приборы из поливинилхлорида. Система отличается малым весом и быстрым выходом в рабочий режим. Однако в литературе отсутствует методика расчета коэффициента теплоотдачи в замкнутом пространстве, образованном поверхностью гибкого нагревателя и ограждающей стеной. На основе анализа зависимостей и экспериментальных данных получены новые критериальные уравнения для расчета коэффициента теплоотдачи для произвольного расположения нагревателей в пространстве. Построена зависимость $\lg \mathrm{Nu} = f(\lg(\mathrm{Gr}\cdot\mathrm{Pr}))$, которая позволяет определить величину коэффициента теплоотдачи для заданной области температуры. Предложен способ интенсификации процесса теплообмена за счет создания искусственной шероховатости. Построен график для определения доли роста теплоотдачи C_K, входящей в критериальное уравнение. Применение искусственной шероховатости позволило увеличить коэффициент теплоотдачи на 28 %, а тепловую мощность нагревательного прибора – примерно на 26 %.

Ключевые слова: полевой госпиталь, система теплоснабжения, коэффициент теплоотдачи, критериальное уравнение, интенсификация

Для цитирования: Иокова, И. Л. Расчет теплообмена на поверхности гибкого теплообменника для применения в мобильных госпиталях / И. Л. Иокова, А. С. Калиниченко // *Энергетика. Изв. высш. учеб. заведений и энерг. объединений СНГ*. 2020. Т. 63, № 1. С. 81–88 https://doi.org/10.21122/1029-7448-2020-63-1-81-88

Introduction

Currently, the world is characterized by quite a large number of military conflicts, man-made disasters, natural disasters. In the XXI century, hundreds of thousands of people died as a result of these disasters, and millions of people were affected. Every year, about 50 thousand people die from various natural disasters in the world. Billions of dollars are spent on disaster relief. In Russia, losses annually reach 60 billion rubles, so only competent actions in emergency situations can save lives and reduce losses [1].

The report of the UN Office for disaster reduction (UNISDR) notes that natural disasters that occurred in the world between 1998 and 2017, led to the death of 1.3 million people (more than half of them – because of earthquakes). According to the Office data, during the same period, the financial losses of world markets due to natural disasters increased by 251 % and amounted to more than 2.9 trillion dollars. Moreover, 77 % of financial losses are attributable to weather-related events [2]. The analysis shows that human losses could be significantly less with rapid first aid. This requires a field hospital located as close to the lesion as possible. Historically, the first field hospitals were designed to provide medical care in combat.

The technology development makes it possible today to produce such mobile hospital, which will have sufficient mobility for delivering to the victims, as well as to function in the immediate vicinity of the epicenter of a natural (man-made) disaster or a war zone [3, 4]. Such hospital, in addition to mobility and good security, should have full autonomy, that is, have an independent source of energy. The heat supply of the new type of field hospital should take into account the likelihood of working in cold conditions (at air temperatures below 15 °C), as well as the possibility of urgent medical care to non-transportable victims in the open air without the construction of temporary structures. Therefore, the creation of an efficient, reliable and simple heating system is an important task.

The heating system can be used for heating not only mobile medical field hospitals, but also for heating any mobile facility. Heat supply of existing field (mobile) hospitals is most often made by means of hot air. Water as a coolant for these purposes is rarely used [5]. Installations for air heating have a sufficiently large mass and take up a lot of space during transportation. Oil-filled radiators are often used for heating and are the most popular household heaters. All oil radiators are equipped with a thermostat that automatically maintains the set temperature. They are used for heating small rooms up to 30 m^2 [6]. Despite a number of advantages, oil radiators consume a lot of electricity and are very slow to enter the mode. Infrared heaters are more effective, but they are more expensive and cannot be used in high humidity [7]. For field hospitals, heating elements should be low cost, easy to transport and install. Based on these requirements, they should be light, flexible enough and provide the necessary thermal performance.

Main part

Currently, when we talk about flexible heating elements, we mean electric heaters [8]. Despite a number of their advantages, electric heaters are difficult and unsafe to use in field hospitals. Of interest are the proposed flexible heating elements made of polyvinyl chloride, which meet Toxicological standards and can be used in medical institutions [9]. The general view of the heating device is shown in Fig. 1a. Due to the novelty of such heating elements, it is necessary to assess the heat exchange coefficient from their surface and to study the possibilities of heat exchange intensification. The coefficient of heat exchange is the most important characteristic of the heat supply system of a mobile hospital, reflecting its efficiency, since the value of this coefficient directly affects the rate of heating of the heated room (tent or pneumatic module). If the surface is heated the air heats up and moves upwards, being replaced from below by cooler air. In the flow a boundary layer is formed near the surface, the thickness of which increases in the direction of the liquid movement. In the initial zone of motion, the boundary layer is laminar and when the thickness of the boundary layer reaches a certain value, the flow regime changes which entail a change in the value of heat exchange coefficient.

When calculating the heat exchange coefficient, it was assumed that the heating of the liquid (hot carrier) to (95–100) $^{\circ}$C is implemented by a vortex heat generator, which has a number of advantages over other sources of hot carrier heating [10, 11].

It is known that the relative amounts of heat and motion transferred to the same element of the surface of a solid body are equal to each other. The amount of heat transferred to a unit of surface per unit of time (specific heat flux), according to Newton's law will be recorded:

$$q_k = \alpha_k \Delta t, \tag{1}$$

where α_k – heat transfer coefficient by convection from liquid to surface, W/(m^2·K); Δt – temperature difference, °C.

In turn, the resistance force referred to this surface unit, i. e. the tangential stress τ at the wall, measures the amount of motion referred to the surface unit. Full stock of heat Q (W) and amount of motion I (kg·m/s^2) [12]:

$$Q = c_p \rho w F \Delta t \tag{2}$$

and

$$I = \left(\rho w F\right) w, \tag{3}$$

where w – absolute velocity of the fluid, m/s.

One can write down the condition of equality of relative quantities of heat and motion (according to Reynolds)

$$\frac{q_k}{Q} = \frac{\tau}{I}.$$

After the transformations (they are omitted), we get the equation taking into account the laminar sublayer

$$\frac{\alpha_k}{c_p \rho w} = \frac{1}{1 + \frac{w_1}{w}\left(\mathrm{Pr} - 1\right)} \frac{\zeta}{8}, \tag{4}$$

where w_1 – fluid velocity at the interface of turbulent flow and laminar sublayer.

The equation (4) we have written establishes the relationship between the intensity of convective heat transfer α_k and the coefficient of hydrodynamic friction resistance ζ.

When calculating flexible heat exchangers, it is necessary to take into account that they can be located not only horizontally or vertically, but also at an arbitrary angle φ between the plane of the device and the normal to the horizontal line. The proposed heating device for the heating system of a mobile hospital has two heating surfaces: outer one – facing the space of the room and inner one – facing the enclosing structures. The inner surface forms channels with the enclosing planes and the heat exchange in which is significantly different from the heat exchange on the outer surface of the device (Fig. 1b). In the first approximation, the cross section of the heating device consists of five parallel pipes, so it is necessary to consider the heat transfer features on these surfaces separately.

The study of heat transfer under the condition of natural convection in a closed space and its contribution to the total thermal performance of the device is of the greatest practical and scientific interest.

In the study of heat transfer in a horizontal gage, we take the size of the slit l as the determining size, and the temperature of the air in the slit t_g as the determining temperature (Fig. 1b). It is necessary to analyze the heat exchange in a confined space to obtain a final formula that takes into account any position of the heating device, as well as determining the most likely position of the heating device. The analysis showed that for this problem (arbitrary location of the heater surface) there are no methods for estimating heat transfer in a confined space.

To increase the heat transfer from the heating device surface and reduce costs on the energy source, it is necessary to consider the method of intensification of surface heat exchange. Taking into account that the proposed heating device for the field hospital heating system is made of polyvinyl chloride, the method of applying artificial roughness to its surface is of the greatest interest. Studies in the air flow performed in [13] show that the optimal roughness provides the increase in heat transfer up to 60–80 %, and the friction resistance increases only by 10 %.

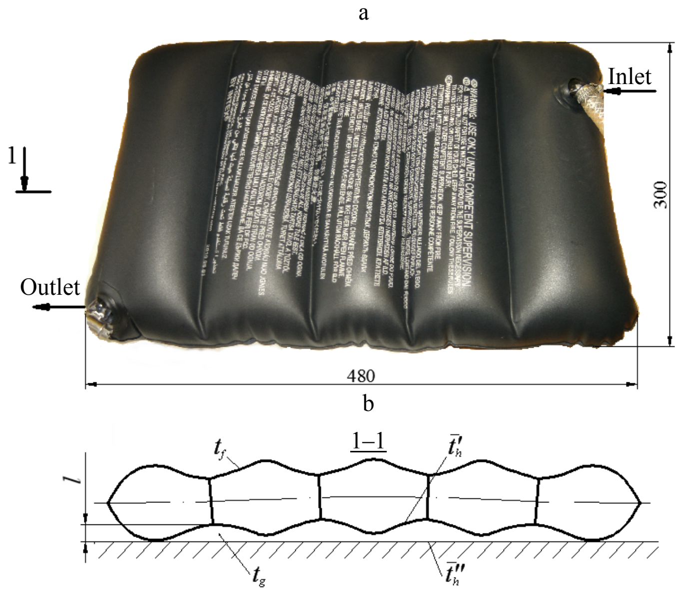

Fig. 1. General view of the heating device (a) and the calculation scheme (b): l – characteristic size; t'_h, t''_h – the temperature of the heat-emitting and heat-receiving surfaces, respectively; t_f – temperature of the free surface; t_g – temperature in the gage

For free convection the heat exchange coefficient is determined from the criterion equation of the form $\mathrm{Nu} = f(\mathrm{Gr}^n \cdot \mathrm{Pr}^m)$, and it is an exponential function. For convenience of processing with application of methods of mathematical statistics it is more convenient to have linear dependence like $y = a + bx$. To proceed to the dependence of the linear form, we take logarithm of both parts of this criterion equation. After processing the experimental data on the heat exchange, it is possible to plot the dependence $\lg\mathrm{Nu} = f(\lg(\mathrm{Gr}^n \cdot \mathrm{Pr}^m))$.

To determine the coefficient of heat exchange from the free surface of a horizontally located heating device under natural convection, we use the criterion equation for $\mathrm{Gr}\cdot\mathrm{Pr} > 8 \cdot 10^6$. Since the heated free surface of the heating device is facing up, we have

$$\mathrm{Nu}_m = 0.195\left(\mathrm{Gr}\cdot\mathrm{Pr}\right)_m^{0.33}.$$

To find the lgNu function for a downwardly oriented hot surface in a cold environment we apply the formula

$$\mathrm{Nu} = 0.24\left(\mathrm{Gr}\cdot\mathrm{Pr}\right)^{0.25},$$

where $4 \cdot 10^3 \le \mathrm{Gr}\cdot\mathrm{Pr} \le 3 \cdot 10^6$.

The results of experimental data processing are shown in Fig. 2 and establish a relationship between the similarity criteria Nu, Gr, Pr. The points resulting from the processing of the experience data are practically laid on one straight line (Fig. 2). We write a mathematical equation for the line corresponding

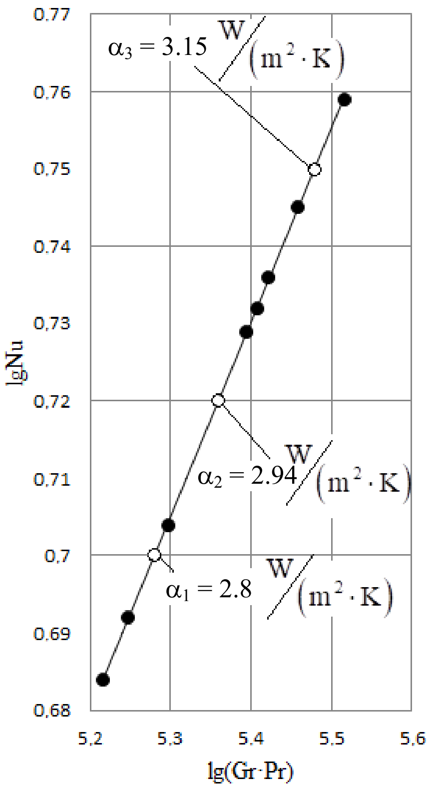

Fig. 2. Graph of dependence according to experimental data for horizontal slit

to the interval of the product lg(Gr·Pr) from 5.216 to 5.516, which was observed in our experiments:

$$\lg\mathrm{Nu} = a_0 + a_1 \lg(\mathrm{Gr}\cdot\mathrm{Pr}). \qquad (5)$$

The coefficients for unknowns were determined by the least squares method. In the final form the calculated criterion equation will be written as

$$\mathrm{Nu} = 0.236(\mathrm{Gr}\cdot\mathrm{Pr})^{0{,}251}. \qquad (6)$$

Expression (6) makes it possible to calculate the intensity of heat exchange coefficient under conditions of natural convection in a confined space (horizontal slit). Calculations have shown that the heat exchange coefficient of the heating device in a confined space (horizontal slit) is significantly less than the heat exchange coefficient on the free surface. However, during the deployment of the field hospital, any position of the heating device is possible, not only horizontal, since there are no locking devices. Accidental location of heating devices in the heated volume when the mobile hospital is put into operation is possible due to the lack of fixing devices. When calculating the heat exchange coefficient from an inclined surface, we can use a formula that is valid for $10^5 < \mathrm{Cr} < 10^9$ and $0 < \varphi < 90°$ [12]:

$$\mathrm{Nu} = 0.48\left(\frac{1+\cos\varphi}{2}\right)\mathrm{Gr}_l^{0.2}. \qquad (7)$$

Taking into account that for Pr = 0.7 the equation $\mathrm{Nu}_0 = 0.68 + 0.513 \times$ $\times \left(\mathrm{Ra}\cdot\cos\varphi\right)^{0.25}$ [14] is valid, we receive after transformations of the equation (7) the following formula considering different positions of the heating device:

$$\mathrm{Nu} = 0.5\left(\frac{1+\cos\varphi}{2}\right)(\mathrm{Gr}\cdot\mathrm{Pr})^{0.25}. \qquad (8)$$

The results of experimental data processing are presented in Fig. 3. Since the arbitrary position of the heating device can be estimated using the probability theory, the formula (8), taking into account the different positions of the heating device, will take the final form

$$\mathrm{Nu} = 0.5\left(\frac{1+p_\Phi(\varphi)}{2}\right)(\mathrm{Gr}\cdot\mathrm{Pr})^{0.25}, \qquad (9)$$

where $p_\Phi(\varphi)$ – probability density.

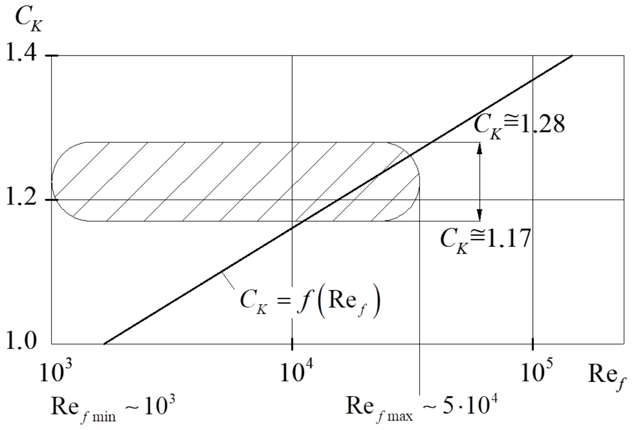

Fig. 3. Graph of evaluation of heat transfer intensification in the presence of artificial roughness

As noted earlier, to improve the thermal performance of the proposed heating device, it is advisable to create an artificial roughness on its surface. Experiments were carried out to determine the effect of roughness on the change in the value of the heat exchange coefficient on the outer surface. Using the results of the full-scale experiments and the data of [15] for the values of $w_f \sim (0.1–1.0)$ m/s; $t_f \sim (30–70)$ °C and $\mathrm{Re}_f = (3000–37000)$, a graphical dependence of $C_K = f(\mathrm{Re})$ is constructed (Fig. 3).

Taking into account the coefficient C_K, the previously obtained equation (9) for the soft surface of the heating device made of polyvinyl chloride could be written in the final form:

$$\mathrm{Nu}_{f_{C_K}} = 0.5 C_K \left(\frac{1 + p_\Phi(\varphi)}{2} \right) (\mathrm{Gr} \cdot \mathrm{Pr})^{0.25}, \qquad (10)$$

where C_K – share increase of heat exchange.

The resulting final criterion equation (10) allows to make the necessary calculations to assess the heat transfer from the surface of the heating device of the heat supply system, taking into account the peculiarities of the position of this device in space. In addition, this equation takes into account the presence of measures to intensify heat transfer in the system "heating device-environment".

The formation of artificial roughness on the surface of the heating device in order to intensify heat transfer increased heat exchange coefficient by 28 %. The heat output of the heater increased to 125.7 W. Calculations have shown that 8 heating devices are enough to heat the module with a volume of 84 m^3 at an indoor temperature of 18 °C and an outdoor temperature equal to (–24) °C.

CONCLUSION

Criterion dependences allowing calculating the heat exchange coefficient from the surface of the heater made of PVC at any of its spatial position are proposed. In order to intensify the heat exchange process, it is proposed to create an artificial roughness on the surface, which allowed increasing the heat exchange coefficient by 28 %, and the power of the heating device – by 25 %. The obtained dependences are of scientific and practical interest for the calculation of heat transfer processes in a closed space.

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Received: 26 June 2019 Accepted: 2 September 2019