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IMPROVEMENT OF THERMAL-HYDRAULIC EFFICIENCY OF MINING POWER EQUIPMENT THROUGH THE APPLICATION OF POROUS FREON STEAM GENERATORS WITH HIGH HEAT CONDUCTIVITY

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Abstract. In the article, various areas of technical application of porous freon steam generators in mining power equipment are described, and explanations why freon coolants can provide a positive energy effect in such facilities are given. The paper presents results of calculations of thermal-hydraulic efficiency of the porous once-through tubular steam generators with freon-12 as a model working fluid in the the laminar flow area and with boundary conditions of the first kind. The smooth-wall cylindrical channels with different diameters were used as the reference surfaces to be compared. The following mode and design parameters were taken as a calculation base: the liquid temperature and pressure on the saturation line at the entry into the channel were: T_{s0}= 110 °C; P_0s = $39{,}9\cdot10^5$ N/m^2.; temperature heads, i.e. a difference between the wall temperature and temperature of the liquid at the entry into the channel were: $\Delta T=T_w-T_{s0}$ = 1 °C; 2 °C; 3 °C; 4 °C; 5 °C; the Reynolds numbers at the entry into the channel were: Re_o = 100; 200; 500; 1000; 2000; 2300; the channel porosities were: θ = 0.7; 0.75; 0.8; 0.85; 0.9. The porous material was metal felt with the copper fiber diameter of 200 microns. The channel diameters were: d =$3\cdot10^{-3}$ m; $4\cdot10^{-3}$ m; $5\cdot10^{-3}$ m; $6\cdot10^{-3}$ m; $7\cdot10^{-3}$ m. On the basis of the performed computational studies, it was concluded that for the conditions of the same mass flow rates of the coolant, with laminar flow, and the same channel diameters, it is possible to achieve a significant reduction in the length of the porous once-through steam generator in comparison with the length of the smooth-wall once-through steam generator. Due to the significantly shorter length, differential pressure for pumping the coolant can be several tens of percent less in porous evaporation channels than in the similar smooth-walled channels. This computational study also made it possible to establish main regularities in dynamics of the energy efficiency coefficients and their dependence on the model mode and design parameters. It was shown, that positive dynamics of the efficiency coefficients of porous steam generators occurs with decrease of the channel diameter and temperature head, as well as with increase of the Reynolds number in the investigated region of coolant laminar flow.

Keywords: thermal-hydraulic efficiency; porous steam-generating channels; coolant, freon-12; boundary conditions of the first kind; laminar flow of coolant.

1. Introduction

Porous high heat conducting materials have long been widely used in various technological equipment. The necessity to solve the important problem of minimizing energy consumption during the operation of mining technological equipment and to use secondary thermal resources of mining technologies makes it possible to use porous high heat conducting materials in this type of equipment as well.

One of the types of special technological equipment which provides operation of the mining complex is refrigeration compressor equipment with freon-based coolants. Such refrigeration equipment can be used during the roadway drivage in order to freeze soils for giving them the necessary mechanical properties. The second example of refrigerating machine use in mining production is the heat pumps for removing heat of mine groundwater. The third example of the use of refrigeration technological equipment in mining production can be air conditioners needed to ensure the required thermophysical parameters of the mine atmosphere in accordance with norms of labor protection standards. The use of low-grade secondary thermal resources in the mining industry assumes freon evaporation with certain properties and, further, supply of the freon vapor to the gas turbine to generate additional electric power. Such an installation consisting of gas turbine, freon vapor condenser and pump supplying liquid-phase freon to the steam generator implements the Rankine thermodynamic cycle.

In all thermodynamic cycles of operation of the refrigeration and low-temperature heat equipment, the process of phase transition of liquid freon to a vapor takes place in the evaporator. When intensifying work processes in the freon evaporators, we can try to reduce consumption of energy required for the operation of the refrigeration equipment.

In so doing, one of the ways of intensifying work processes in freon evaporators is to include porous high heat conducting inserts to their design. On the one hand, the inserts intensify the heat transfer processes during freon evaporation, meaning that freon is evaporated along the shorter length of this device, compared to smooth-walled channels. On the other hand, this increases hydraulic resistance when freon is pumped through the evaporator. This fact necessitates finding such rational mode and design parameters for these devices, at which the gain in heat transfer could exceed the loss in hydraulics.

It should be mentioned that one work [1] is known in the foreign literature which is devoted to experimental study of thermal-hydraulic efficiency of the porous steam generators. In this research, carbon dioxide (CO_2) was used as a working coolant, and sand-gravel mixture was used as a porous material. The authors of the work failed to find positive values of thermal-hydraulic efficiency of such porous evaporator. This can be explained by the fact that, on the one hand, sand-gravel mixture has relatively low heat conductivity, and, on the other hand, sand-gravel mixture, or backfill, features low porosity, which causes high hydraulic resistance of the system. Based on this, we can try to modernize this porous evaporator by using a porous high heat conducting insert in the form of a copper metal-fiber material with high porosity.

Besides, type of coolant used can also influence positive values of the thermal-hydraulic efficiency of porous steam generator. Thus, in [2], the thermal-hydraulic efficiency of porous copper metal-fiber once-through steam generators with water as a coolant was numerically studied. In this work, positive values of the coefficient of energy efficiency calculated as the ratio of differential pressures of the compared reference smooth-walled evaporator and the porous evaporator under the consideration, were not found. At the same time, the authors obtained positive values of coefficients of geometric efficiency determined as a ratio of the lengths of the compared smooth-walled and porous channels. This feature can be explained by the fact that the water coolant has a high value of the specific heat of vaporization and, therefore, for the evaporation of the coolant in a once-through steam generator, a long channel length is required, which, in turn, causes a great hydraulic resistance and, as a result, negative values of the energy coefficient of the thermal-hydraulic efficiency of such systems.

In the case of using freons as the working substance of porous evaporators, it is possible to obtain positive values of the energy coefficients of thermal-hydraulic efficiency, since freons have a relatively low specific heat of vaporization, which can require a short evaporator length and a small differential pressure in the porous steam generator compared to a smooth-walled freon once-through steam generator.

This article is devoted to the computational study of the thermal-hydraulic efficiency of porous copper metal-fiber once-through steam generators of circular cross section in in the laminar flow area of freon-12 coolant in the compared smooth-walled once-through steam generators and under boundary conditions of the first kind. Note that a small number of the above-mentioned researches of thermal-hydraulic efficiency of porous steam generators is due to the fact that the process of studying this process is rather complicated, which explains that there are only a few publications in this area of research.

2. Formulation of the problem

In the course of creating the calculation programs, the following calculation formulas and ratios were used. To calculate heat transfer in cylindrical smooth-walled channel, formula of S.N. Bogdanov [3] was used for calculating the heat transfer coefficient averaged over the length of the evaporation when freons boil in the channels. To calculate heat transfer for the case of vapor-liquid mixture flowing through the porous high heat conducting media, the ratio obtained by I.V. Kalmykov [4] was used to calculate the coefficient of volumetric intraporous heat transfer. The differential pressure during the evaporation of freon in cylindrical smooth-walled channel was calculated according to the simplified Bo Pierre equation for complete evaporation of coolant [3]. Hydraulic resistance in porous channels with two-phase vapor-liquid flow of the coolant was calculated by the method similar to the Lockhart-Martinelli technique [5]. This technique was applied by Yu.A. Zeigarnik and I.V. Kalmykov [4], [6] to the two-phase vapor-liquid flows through the porous high heat conducting media. The formulas from this technique were used in the course of the computational and numerical studies.

3. Results

To study the possibility of using porous steam generators as part of refrigerating machines used in mining industry, the thermal-hydraulic efficiency of the porous once-through tubular steam generators with freon-12 coolant was calculated.

Parameters of the thermal-hydraulic efficiency included: the ratio of differential pressures for pumping the evaporating coolant through the smooth-walled and porous channels $\Delta P_{sm}/\Delta P_{por}$; the ratio of the lengths of the smooth-walled and porous channels l_{sm}/l_{por}, and the ratio Q/N, where Q was the amount of heat absorbed by the channel during the evaporation of the liquid, N was the power consumed for pumping the coolant.

Smooth-walled cylindrical channels with various diameters were used as reference surfaces to be compared. Metal felt was considered as a porous high heat conducting insert.

The mode and design parameters were changed in the course of calculations within the following ranges: temperature and pressure of the liquid at the entry into the channel were T_{s0} = 110 °C; P_0s = $39.9\cdot10^5$ N/m^2; difference between temperature of the channel wall and temperature of the liquid at the entry into the channel was

T_w–T_{s0}=1÷5 °C; Reynolds number at the entry into the channel was Re_0 = 100÷2300; the channel porosity was Θ = 0.7÷0.9; the channel diameter was d=3÷7 mm.

In the course of the computational studies, it was found that to achieve complete evaporation of the coolant, porous channels can be several times shorter than smooth-walled channels with the same diameter. At the same time, with the same flow rate of the coolant, differential pressure for pumping coolant through the porous evaporation channels can be several tens of percent less than through the similar smooth-walled channels due to a much shorter length. The calculations show that thermal-hydraulic efficiency of the porous channels increases with decrease in the diameter of the studied channels and with decrease in the difference between the temperature of the channel wall and the temperature of the liquid at the entry into the channel, which indicates that porous evaporation channels can be effectively used to remove low-potential heat. Data of graphical processing of calculation results are shown in fig. 1–10. An increase in porosity leads to an increase in the coefficients of energy efficiency and a decrease in the coefficients of geometric efficiency.

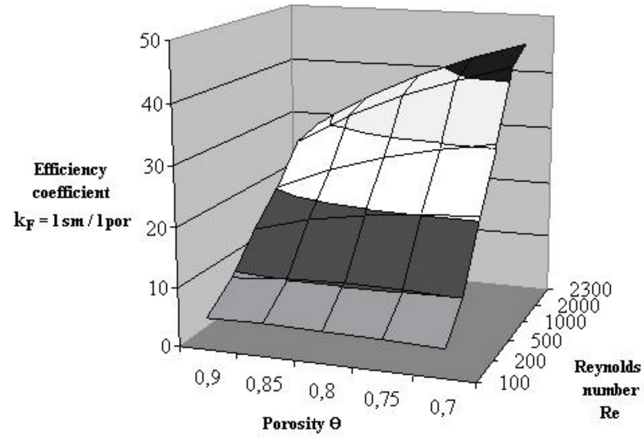

Figure 1 – The value of the geometric coefficient of efficiency of the porous steam generating channel $k_F=l_{sm}/l_{por}$ (T_{s0}=110 °C; d=4 mm; ΔT=4°C)

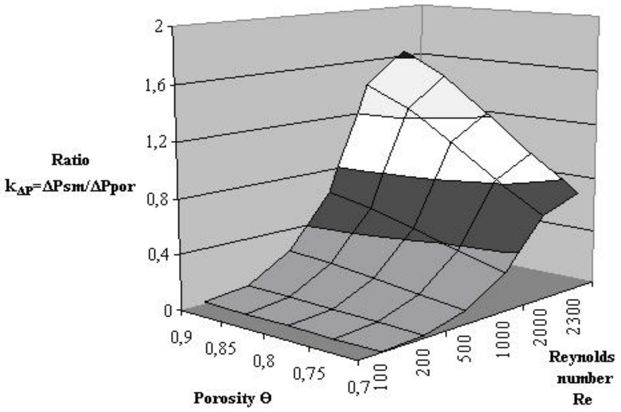

Figure 2 – The ratio of pressure drops in porous and smooth-walled steam generating channels $k_{\Delta P}=\Delta P_{por}/\Delta P_{sm}$ (T_{s0}=110 °C; d=4 mm; ΔT=4°C)

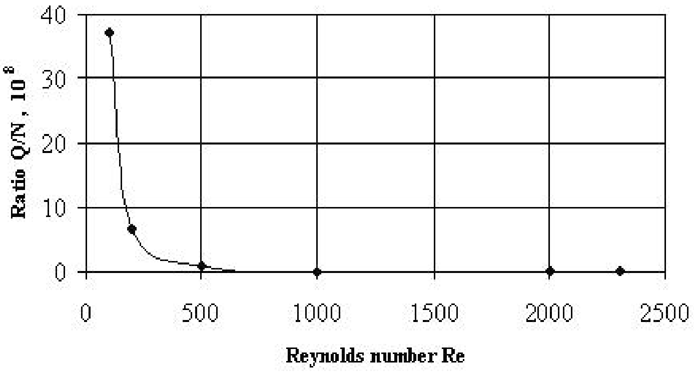

Figure 3 – Ratio of Q/N, 10^8 for a smooth-walled steam generating channel ($T_{s0}=110$ °C; $d=4$ mm; $\Delta T=4$°C)

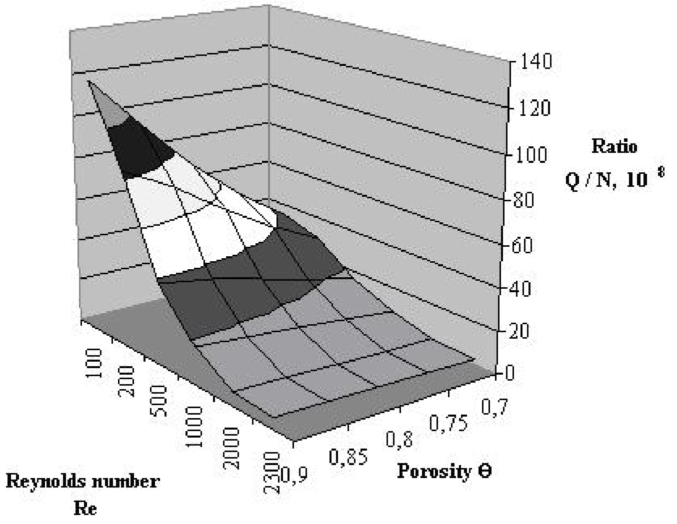

Figure 4 – Ratio of Q/N, 10^7 for a porous steam generating channel ($T_{s0}=110$ °C; $d=4$ mm; $\Delta T=4$°C)

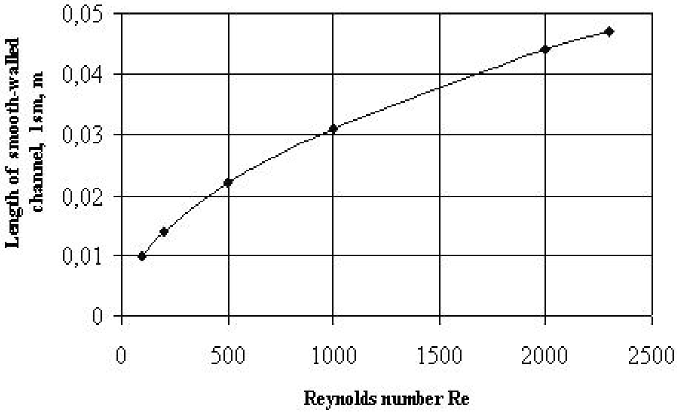

Figure 5 – Length of smooth-walled steam generating channel l_{sm}, m ($T_{s0}=110$ °C; $d=4$ mm; $\Delta T=4$ °C)

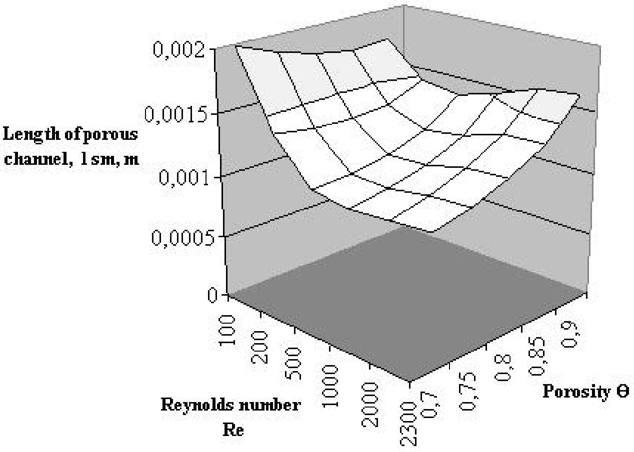

Figure – 6 Length of the porous steam generating channel lpor, m
($T_{s0}=110$ °C; d=4 mm; $\Delta T=4$ °C)

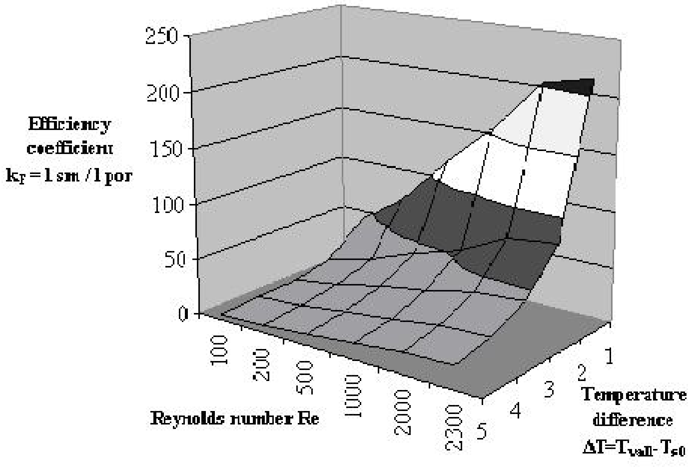

Figure 7 – The value of the geometric coefficient of efficiency of the porous steam generating channel $k_F=l_{sm}/l_{por} = f(Re, \Delta T)$; ($T_{s0}=110$ °C; d=4 mm; $\Theta=0{,}9$)

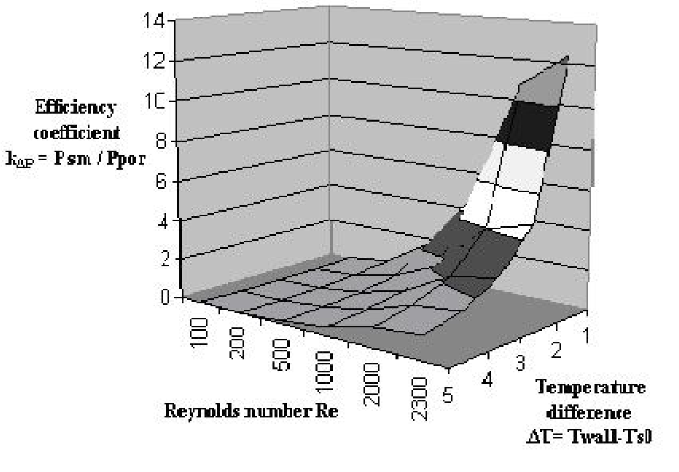

Figure 8 – The ratio of pressure drops in porous and smooth-walled steam generating channels $k_{\Delta P} = \Delta P_{por}/\Delta P_{sm} = f(Re, \Delta T)$; ($T_{s0}=110$ °C; d=4 mm; $\Theta=0{,}9$)

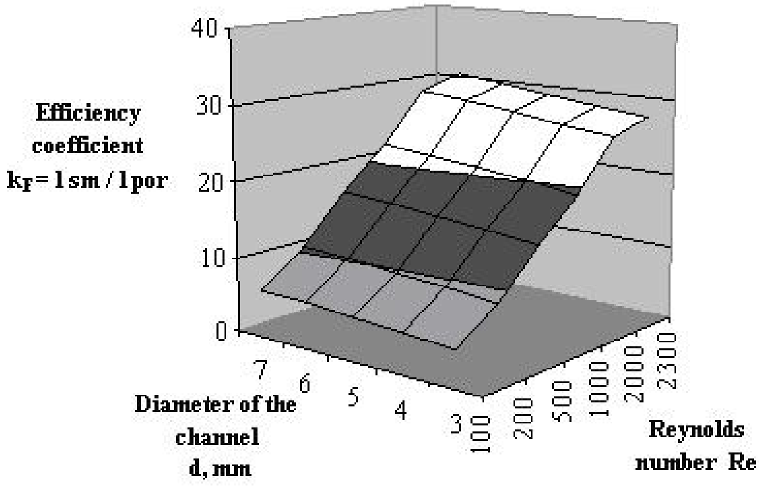

Figure 9 – The value of the geometric coefficient of efficiency of the porous steam generating channel $k_F=l_{sm}/l_{por}$ = f(Re, d); (T_{s0}=110 °C; ΔT= 4°C; Θ=0,9)

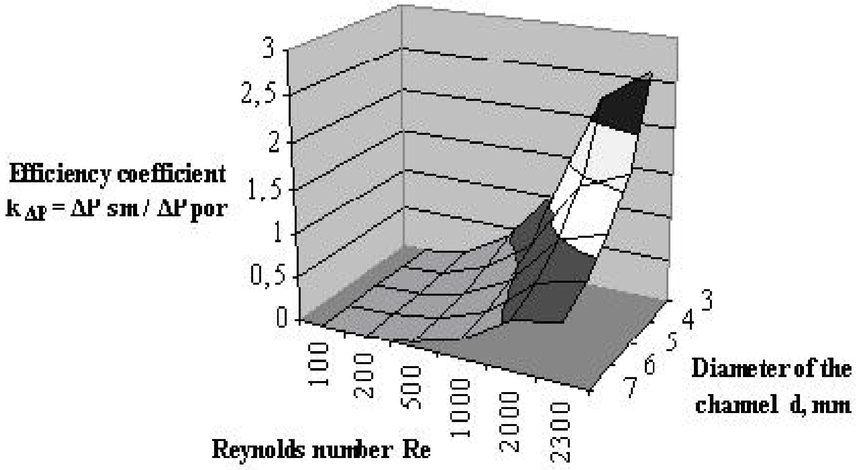

Figure 10 – The ratio of pressure drops in porous and smooth-walled steam generating channels $k_{\Delta P} = \Delta P_{por}/\Delta P_{sm}$ = f(Re, d); (T_{s0}=110 °C; ΔT=4°C; Θ=0,9)

4. Conclusions

Based on the results of the performed computational studies, the following conclusions can be drawn.

When using porous metal-fiber highly thermally conductive inserts in evaporators of refrigeration machines, which have ideal thermal contact with the channel wall, it is possible to obtain positive values of both geometric and energy efficiency coefficients.

A positive increase in the efficiency coefficients of porous steam generators is affected by a decrease in the channel diameter and temperature difference between the channel wall and the coolant temperature at the channel inlet, as well as an increase in the Reynolds number in the investigated laminar region of coolant flow.

An increase in the porosity of the channel has a positive effect on the energy efficiency coefficient, but decreases the geometric efficiency coefficient of porous freon steam generators.

The performed computational-theoretical studies are the basis for experimental verification of the results obtained.

A general analysis of the results of the study indicates a fairly high efficiency of the use of porous freon steam generators in mining equipment.

The nature of the data obtained as a result of calculations indicates the need for similar studies in adjacent speed regimes of coolant flow.

REFERENCES

1. Tarawnech, M., Alshiqirate, A.S. and Jawarnechn, A.M. (2014), "Effect of Darcy, Reynolds and Prandtl Numbers on the Performance of Two-Phase Flow Heat Exchanger Filled with Porous Media", *Heat Transfer – Asian Research*, Vol. 43, Issue 8, December, pp. 749–758. https://doi.org/10.1002/htj.21117

2. Lukisha, A. P. (2020), "Calculation of the thermohydraulic efficiency of porous direct-flow steam-generating channels", *Journal of Engineering Physics and Thermophysics*, Vol. 93, No. 5, September, pp.1096–1107. https://doi.org/10.1007/s10891-020-02210-8

3. Gogolin, A.A., Danilova, G.N., Azarskov, V.M. and Mednikova, N.M. (1982), *Intensifikatsija teploobmena v ispariteljah holodilnyh mashin* [Intensification of heat transfer in evaporators of refrigeration machines], in Gogolin, A.A. (ed), Legkaya I pishchevaya promyshlennost, Moskow, USSR.

4. Kalmykov, I.V. (1987), Heat transfer and hydrodynamics at motion of the steam-liquid flow in porous media, Abstract of Ph.D. dissertation, Thermophysics and molecular physics, Institute of High Temperatures of the Academy of Sciences of the USSR, Moscow, USSR.

5. Lockart, R. W. and Martinelli, R.C. (1949), "Proposed correlation of data for isothermal two-phase, two-component flow in pipes", *Chemical Engineering Progress*, Vol. 45(1), pp. 39–48.

6. Zeigarnik, Yu. A. and Kalmykov, I.V. (1985), "Experimental study of the hydraulic resistance of porous structures at adiabatic motion steam-water mixture", *Teplofizika vysokih temperatur*, Vol. 23, no. 5, pp. 934–940

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ПІДВИЩЕННЯ ТЕПЛОГІДРАВЛІЧНОЇ ЕФЕКТИВНОСТІ ГІРНИЧОГО ЕНЕРГЕТИЧНОГО УСТАТКУВАННЯ ЗА РАХУНОК ЗАСТОСУВАННЯ ПОРИСТИХ ВИСОКОТЕПЛОПРОВІДНИХ ФРЕОНОВИХ ПАРОГЕНЕРАТОРІВ

Лукіша А.П., Лукіша М.А., Кірсанов М.В.

Анотація. У статті описані різні галузі технічного застосування пористих фреонових парогенераторів у гірничому енергетичному обладнанні, а також показано, чому фреонові теплоносії можуть дати позитивний енергетичний ефект у подібних пристроях. В роботі представлені результати розрахунків теплогідравлічної ефективності пористих прямоточних парогенераторів з модельною робочої рідиною фреон-12, в ламінарній області руху теплоносія і при граничних умовах першого роду. В якості порівнюваних еталонних поверхонь використовувалися гладкостінні циліндричні канали різних діаметрів. В якості розрахункової бази були взяті такі режимно-конструктивні параметри: температура рідини на лінії насичення на вході в канал T_{s0}= 110 °C; $P_0s = 39{,}9 \cdot 10^5$ Н/м^2. Температурний напір - різниця між температурою стінки і температурою рідини на вході $\Delta T = T_w - T_{s0}$ = 1 °C, 2 °C, 3 °C, 4 °C, 5 °C. Число Рейнольдса на вході в канал: Re_o = 100, 200, 500, 1000, 2000, 2300. Пористість каналу θ = 0,7; 0,75; 0,8; 0,85; 0,9. Пористий матеріал - металовойлок з діаметром мідних волокон 200 мкм. Діаметр каналу $d = 3 \cdot 10^{-3}$ м; $4 \cdot 10^{-3}$ м; $5 \cdot 10^{-3}$ м; $6 \cdot 10^{-3}$ м; $7 \cdot 10^{-3}$ м. На підставі проведених розрахункових досліджень був зроблений висновок, що для умов однакових масових витрат охолоджувача, при ламінарному режимі руху, і однакових діаметрах каналів, можна домогтися істотного скорочення довжини пористого прямоточного парогенератора в порівнянні з гладкостінним прямоточним парогенератором. За рахунок значно меншої довжини пористі випарні канали можуть мати перепад тиску на прокачування теплоносія на кілька десятків відсотків менше, ніж аналогічні гладкостінні канали. Дане розрахункове дослідження також дозволило виявити основні закономірності в поведінці енергетичних коефіцієнтів ефективності та їх залежність від режимно-конструктивних параметрів моделі. Було показано, що на позитивний зріст коефіцієнтів ефективності пористих парогенераторів впливають зменшення діаметра каналу та температурного натиску між стінкою каналу та температурою теплоносія на вході в канал, а також збільшення числа Рейнольдса в досліджуваній ламінарній області руху теплоносія.

Ключові слова: теплогідравлічна ефективність; пористі парогенеруючі канали; теплоносій фреон-12; граничні умови першого роду; ламінарний режим руху теплоносія.