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Sensitivity Analysis on Thermal Performance of Gas Heater with Finned and Finless Tubes using Characteristics-based Method

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ABSTRACT

Natural gas must be preheated to prevent phase change and gas hydrate in pressure reduction stations. This paper aims to investigate the effect of the fins of gas tubes and their configuration, arrangement, and shape on the heat transfer and thermal efficiency of gas. To conduct a parametric study, two tube cases with fins and without fins, and in the finned case for the fin's configuration, two longitudinal and circular arrangements, and the formation of the fins, two solid and interrupted forms were analyzed. Also, three types of cross-sections, including rectangular, convergent parabolic, and divergent parabolic, for the shape of the fins have been studied. For this simulation, the three-dimensional, incompressible, and steady flow was considered, and for analysis and discretization of convective heat equations, the characteristic-based method was applied. FORTRAN software was also used to implement and solve the equations. The results show that in solid and interrupted fins and increasing the number of fins in parallel, the dimensionless heat transfer coefficient increases. Also, the dimensional heat transfer coefficient decreases with increasing the ratio of fin height to the tube's diameter. Also, the most significant heat transfer improvement was related to the divergent parabolic cross-section.

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1. INTRODUCTION

Optimal energy consumption is the main issue in recent years, and researchers had many studies in this field [1]. The consumption of natural gas as a fuel in the heaters of the pressure reduction stations has drawn attention to the use of solutions to reduce fuel consumption and increase the efficiency of heaters. Researchers have proposed numerous methods and, in some cases, implemented them. Recycling power from the chimney outlet, using various fluids to transfer heat, modifying the combustion chamber, using a catalytic heater, using nanofluids, solar cells, temperature control equipment for the output of the heater, and controlling fuel consumption are some of the solutions. Using nano-fluids is another way to increases the heat transfer rate[2]. Natural gas is one of the primary sources of energy called sour gas when extracted from tanks containing impurities such as H_2S and CO_2. Before consumption, during the gas sweetening process in the gas treating unit, acid gases are separated, and sweet gas is obtained [3]. In 2012, 24% of the world's electricity was generated by natural gas compared to other energy sources such as oil, coal, nuclear energy, hydroelectricity, and renewable energy sources [4].

Free convection heat transfer is a common physical phenomenon that is important in the design and operation of heat exchangers. Researchers have studied different types of fins in vertical and horizontal plates and cylinders and their effect on increasing free convection. Ahmadi et al. [5] examined and compared the transfer of free transfer heat from vertical heating wells with solid and interrupted longitudinal fins. Their research included a comprehensive empirical and numerical study of the effect of interrupting fins and the longitudinal distance of two fins on heat transfer. Sajedi et al. [6] examined the optimal number of longitudinal fins in a vertical

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cylindrical heat exchanger. The temperature distribution of the heat exchanger and the total heat transfer indicate the optimal number of fins to increase the heat transfer. Sebastian and Shine [7] studied layered free convection around a heated cylinder with or without a horizontal barrier. Numerical modeling consists horizontal barriers above and below the cylinder at different vertical distances, and the finite volume method was used to solve two-dimensional governing equations. Innella and Rodgers [8] investigated the Benefits of a Convergence between art and engineering by compiling and analyzing a review of the literature and creative works spanning from the renaissance to contemporary art; their paper presents the potential benefits of combining engineering and art research. Fazelabdolabadi and Golestan [9] developed a Bayesian framework to quantify the absolute permeability of water in a porous structure from the geometry and clustering parameters of its underlying pore-throat network. Bayareh et al. [10] studied the effects of stator boundary conditions and fin geometry on the efficiency of a scraped surface heat exchanger numerically. Matsunaga and Sumitomo [11] studied pressure loss and heat transfer in a double-tube type heat exchanger with rotating fins. They used the corn syrup water solution as a test process fluid. Shahsavar Goldanlou et al. [12] studied the turbulent forced convection heat transfer of Fe_3O_4/-CNT/water hybrid nanofluid (HNF) in a heat exchanger (HE) equipped with fin-shape turbulators. They solved the 3D governing equations with the SIMPLE algorithm and solution domain by employing the control volume method (CVM). Zhang et al. [13] studied a gas engine-driven heat pump (GEHP) performance experimentally for space heating and cooling and investigated the effect of critical parameters on system performance under both cooling and heating modes. Kostikov and Romanenkov [14] performed an estimating the convergence rate of an algorithm for numerically solving the optimal control problem for the three-dimensional heat equation. A variety of longitudinal and peripheral fins are used to increase the heat transfer of free convection. Kuma et al. [15] modeled the transient convection of a horizontal fin tube inside a furnace in OpenFOAM software. They studied the effect of fin diameter, the ratio of fin diameter to tube diameter, furnace height, and ambient temperature difference, and the surface area of the tube on heat transfer by considering 8 circular fins in the middle of a tube with an outer diameter of 24.9 mm. Kiatpachai [16] studied the effect of serrated circular fins on the hydrothermal performance of fin-tube heat exchangers. Considering the physical parameters, they experimented with several arrays of fins. A specific type of longitudinal Fin was investigated in Lorenzini's work [17]. They introduced longitudinal T-shaped fins to increase the cooling rate of a horizontal cylinder. The purpose of their study was to reduce the maximum difference between the temperature of the cylinder and the environment.

Another way to reduce energy consumption in heaters at a pressure reduction station is to release gas at the minimum acceptable temperature. The minimum temperature required to prevent gas condensate and hydrate formation can be calculated using thermodynamic relations according to the thermo-physical conditions of natural gas and the pressure drop rate. Using this idea, Ashouri et al. [18] Proposed a temperature control system to determine the gas output conditions. There is not any analytical solution for the thermo-flow governing equation in general. As a result, experimental and numerical methods were used to simulate flows with heat transfer in different cases. An experimental method is expensive, and most of the simulations in the recent decade are done numerically by investigators [19-21].

In this paper, for the first time, it is proposed to use different fins for a shell-tube heat exchanger that contains gas transmission tubes. Numerical simulations are done by a new characteristics-based method that the authors introduced in their previous works [22, 23]. This characteristic-based numerical scheme was developed for three-dimensional flow [24]. As a result, it can be used in the three-dimensional flow with heat transfer. According to previous research in improving heat transfer from horizontal cylinders in pressure reduction station heaters, the suitable types of fins and their thermal role are studied in the present study. The proposed fins have been in different shapes and dimensions. The Fin effect on the improvement of free convection from the tubes and the increase of heat transferred to the gas inside the tube have been studied. Optimum cases that have high efficiency have been found and reported in this work. The study originated and was designed based on a need in natural gas stations to prevent phase change and hydrate formation. In the introduction, the purpose of the article was presented by stating the problem and reviewing the literature. In the modeling section, the geometric model of the system and mathematical equations will be extracted, and after stating the initial conditions and boundary conditions, the solution method will be expressed. Finally, after the simulation and parametric analysis of the model, the results of the simulation and analysis will be presented and discussed in the results section.

2. MATERIALS AND METHODS

The steps of the research process, including research methodology as a flowchart are shown in Figure .

2. 1. Geometric Modeling As seen in Figure 2, to the parametric analysis of the effect of fins on gas tubes

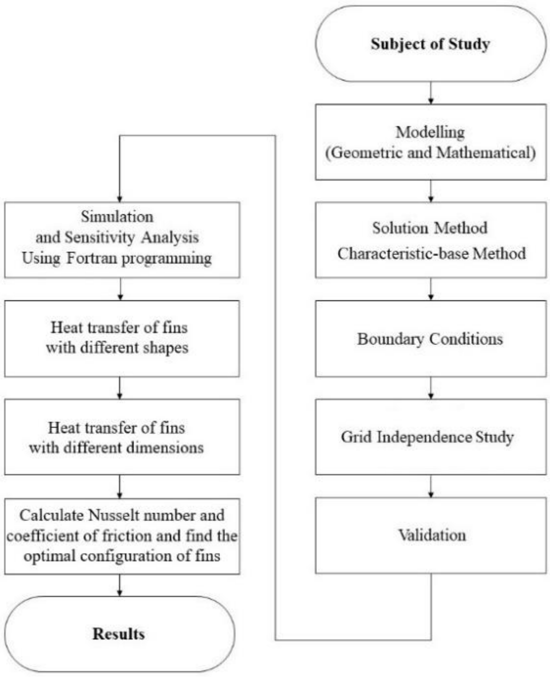


Figure 1. Research process steps

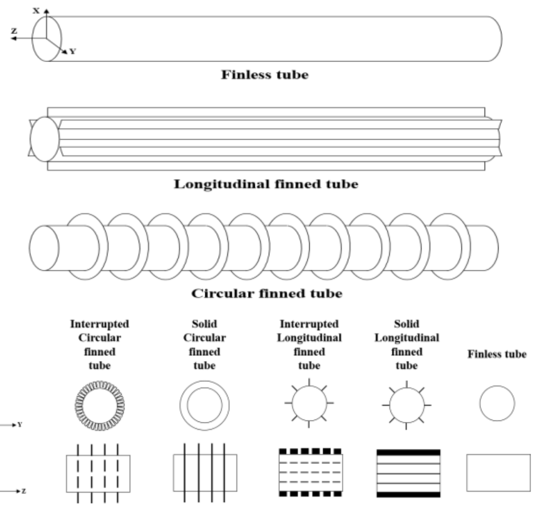


Figure 2. Finless and finned tubes configurations

heat transfer, two tube-cases with fins and without fins, and in the finned case for the fins configuration, two longitudinal and circular arrangements, And for the fins formation of the fins, two solid and interrupted forms are studied. As shown in Figure , three shapes, including rectangular cross-section, convergent parabolic, and divergent parabolic for the fins, are also examined.

2. 2. Mathematical Modeling The governing equations of the incompressible fluid along with heat transfer are as follows:

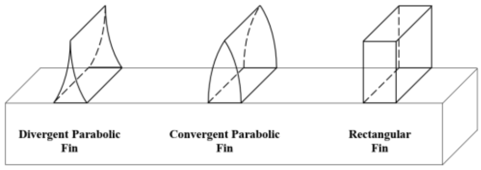


Figure 3. Fins sections and shapes

$$\vec{\nabla}\vec{V} = 0, \ \frac{D\vec{V}}{Dt} = -\frac{\vec{\nabla}p}{\rho} + \upsilon\nabla^2\vec{V}$$
$$\frac{DT}{Dt} = \frac{k}{\rho C_p}\nabla^2 T. \quad (1)$$

In the above equation, V is the velocity, p is the pressure, T is the temperature, ρ is the density, ϑ is the kinematic viscosity, g is gravity acceleration, and C_P is the thermal coefficient. In free and mixed convection, density is not constant, but the Boussinesq assumption can be used. The governing equations are solved numerically by a new finite volume method. A new three-dimensional characteristics-based scheme is used to obtain convective fluxes [24]. The used numerical method is one of the novel numerical methods. Due to the use of virtual waves propagating inside the incompressible fluid, it is more stable to find convective fluxes than the averaging method. Convective terms at the cell boundary were calculated in the finite volume method. The second-order averaging scheme is used to calculate viscous fluxes, and the fifth-order Runge-Kutta method is applied to time marching [23, 25]. For validation, the accuracy of the numerical results of the free convection heat transfer from a horizontal tube enclosed in the chamber was examined. Nusselt numbers at different Rayleigh numbers were obtained by the explained numerical method and are compare by Cesini et al. [26] results. Cesini et al. [26] performed a three-dimensional experimental work. Air is used as the working fluid. The interval vertical walls were made of aluminum and cooled by coolant fluid. Plexiglass made the top and the bottom walls. The last vertical wall was made of glass to allow optical work. After validating the numerical model and studying the effect of the fins on heat transfer, simulation was performed for a horizontal tube enclosed in the chamber, and the effect of the fins on heat transfer is investigated. Cesini et al. [26] considered the horizontal tube enclosed in the chamber containing the air and examined the effect of the Rayleigh number and the chamber's geometry on the heat transfer coefficient. Their study was experimental, and they used numerical analysis to ensure the accuracy of the experiments. The temperature of the tube was constant and kept above room temperature. The temperature of the surrounding walls was assumed to be constant and uniform. Neumann boundary condition was applied at the upper level of the chamber, and the overall heat transfer coefficient from the upper level was $10\, W/m^2k$. This comparison is displayed at Table 1. Good agreement between results was observed. According to the results the maximum error was 9.2%. No slip conditions were considered at wall. The velocity and temperature are given at the inlet, and pressure is calculated by second-order extrapolation. The pressure is given at the outlet, and temperature and velocities are calculated by second-order extrapolation

This problem is considered a steady state problem. Hence it does not need the real initial condition. The initial condition in this numerical simulation is defined as inlet and outlet boundary conditions. After numerical simulations and determining the temperature, pressure, and velocity fields, the Nusselt number and friction coefficient were calculated numerically by second-order methods. The Nusselt number and the friction coefficient are compared, and the fin efficiency is determined. Finally, the optimum fin is introduced by comparing the fin efficiency. Experimental and numerical studies focused on calculating the average Nusselt number of cylinders calculated from the following equation.

$$Nu = \left(\frac{\partial T}{\partial r}\right)_{r=D/2} \frac{D}{\theta}, \quad \overline{Nu} = \frac{1}{\pi D}\int_0^{\pi D} Nu.ds \qquad (2)$$

In the above equation, Nu is Nusselt number, $\overline{Nu}$ is the mean Nusselt number, D is the diameter of the tubes. The heater has a length of 5600 mm and a diameter of 2100 mm. The thickness of the applied fins on the tubes is 5 mm. In Figure , the position of two middle tubes relative to the fire tube is the most exposed to heat. Also, the close distance between the tubes makes it difficult to dissipate heat from the two pipelines. Therefore, the two middle tubes have the most critical conditions for heat load tolerance and heat transfer limitation. One of these two tubes and the fluid around it is intended for modeling, and its results can be generalized to other tubes collections. The used grid is shown in Figure . A tetrahedron grid is used in this work, and due to the boundary layer effect, the velocity and temperature gradient is high near the wall. Then clustering near the wall is done in this grid to improve the accuracy of the results.

The heater's walls are thermal insulation to reduce energy loss. If the torch operates continuously at its rated load, constant heat flux is transferred from the fire tubes to the fluid. Applying a constant flux to the set keeps the

TABLE 1. Comparison results of mean Nusselt number of cylindrical with Cesini results [26]

Rayleigh numbers	Present paper	Cesini Results [26]	Difference, %
1300	29.2	36.2	9.2
2400	57.2	61.2	5.1
3400	67.2	77.2	6.3

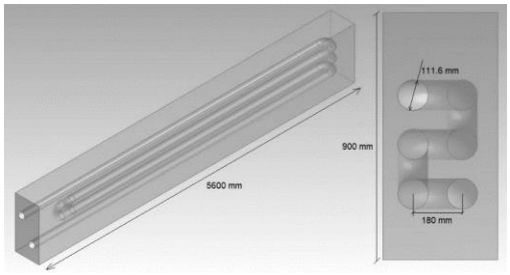


Figure 4. The geometry of the tube position

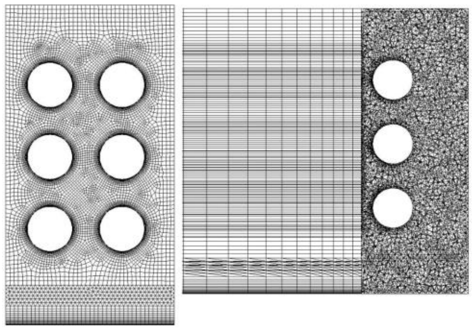


Figure 5. The front cross-section (left) and lateral cross-section (right) of grid

water bath temperature constant at about 80°C. The outlet temperature of the heater should also be higher than the dew point of the water. During the year, the inlet and outlet temperatures of natural gas can be assumed to be 10°C and 38°C, respectively. In the present simulation, the internal surface temperature of the tubes is assumed to be the average gas inlet and outlet temperature, 24°C. If the Fin is used, the outer surface of the tube and the fins is in heat exchange with the surrounding convection medium. The front, rear, and top panels are insulated. Fixed heat flux is applied from the low level. The initial velocity field at the computational domain is zero, and the walls are subject to non-slip conditions. Rayleigh numbers are between 10^9 and 10^{11} according to the industrial data.

3. RESULTS AND DISCUSSION

The enclosed horizontal cylinder-shaped tube in the chamber is modeled. Grid independence for finless tube case at Rayleigh number of 750,000 in four different grid forms studied. The average Nusselt numbers of the tube are obtained in each case and are plotted in Figure 1. The number of elements was selected to be 250,000 for calculations.

In this section, the effect of applying two types of longitudinal and peripheral fins on heat transfer has been studied. The development of heat flow and heat transfer

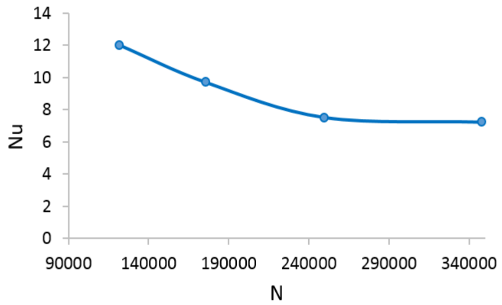
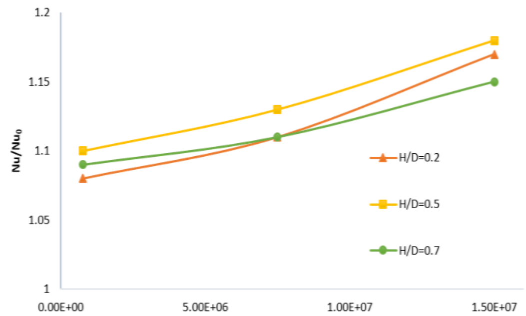


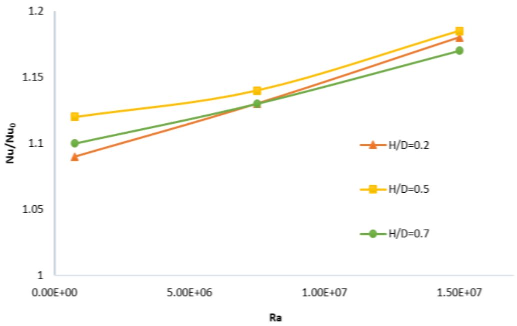
Figure 1. Grid independence study of the finless tube for Ra=750,000

for three large Rayleigh numbers in the layered heat transfer range was studied. The Rayleigh numbers are 750,000, 7,500,000, and 15,000,000, respectively, corresponding to the temperature differences of 1°C, 10°C, and 20°C between the tube and the environment. Two different arrays are modeled for each type of Fin. A comparison is made between the Nusselt numbers of different modes with a tube without a fin. The ratio of the Nusselt number for the finless and with finned case is shown in Figure 2. An increase in 8 to 18 percent and 7 to 16 percent for the dimensionless heat transfer coefficient due to solid and interrupted fins can be seen in the range of Rayleigh numbers studied. In the modeled geometry, the ratio of H / D = 0.5 has the optimum improvement on heat transfer, and its effect increases with increasing Rayleigh number. As the ratio of the height of the Fin to the diameter of the tube increases, the existence of the fins acts as a heat trap and prevents the flow of stagnation. For this reason, the trend of increasing the heat transfer coefficient for H / D = 0.7 is reduced by the Rayleigh number. In this case, the use of 4 and 2 fins increases 10 to 17% and 8 to15% in the dimensionless heat transfer coefficient. It can be concluded that the use of fins to improve the heat transfer of free convection is a function of the geometry of the fins, the dimensions and number of fins, and the Rayleigh number.

In the indirect water heater bath, the set is under free convective heat transfer. In the following, the effect of using two types of fins with different arrays on improving heat transfer from the surrounding fluid to the tube wall has been studied. Average Nusselt number of the pipeline in the presence of longitudinal and circular fins with an increase compared to the finless case. Figures 8-10 show the average Nusselt number ratio of the finless to fin mode for the three rectangular sections, convergent and convergent, respectively. An increase in 3 to 20% is seen for the dimensionless heat transfer coefficient. Among the three cases selected for fin height, H = 15 mm has the highest increase in noise. The fins with a divergent parabolic profile are optimum heat transfer improvement. The heat enters the Fin from the wide surface in contact with the fluid and travels through it to the narrow section leading to the tube. According to the principle of energy conservation, the input heat to the Fin and the output heat are equal; therefore, the heat flux coming out of the Fin is larger than the heat flux entering it, and a larger Nusselt number is obtained at the base of the Fin.



(a)



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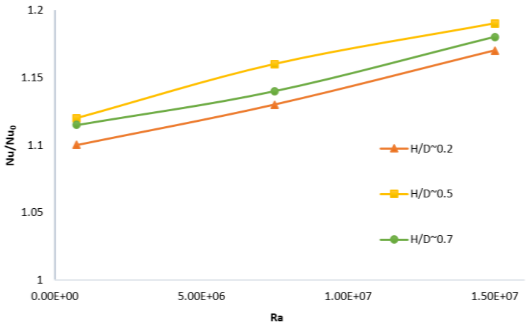

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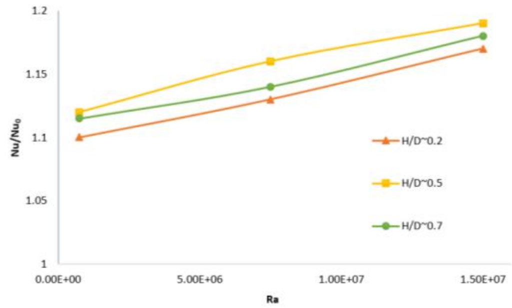

(d)

Figure 2. Average Nusselt number of finned tube relative to the finless tube (a) Solid longitudinal (b) Interrupted longitudinal (c) Quadruple circular (d) Dual circular

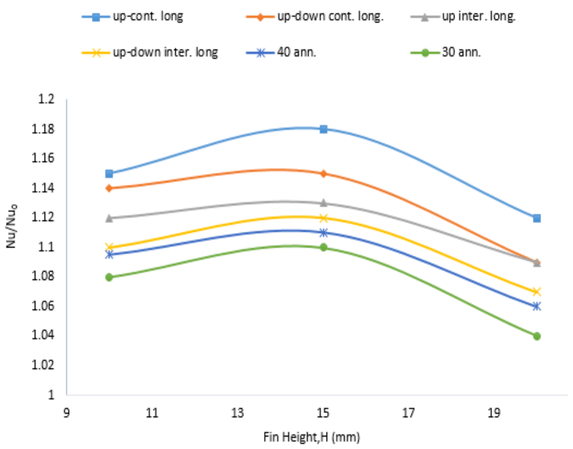

Figure 3. Average Nusselt number of finned tube relative to the finless tube with rectangular shaped fins

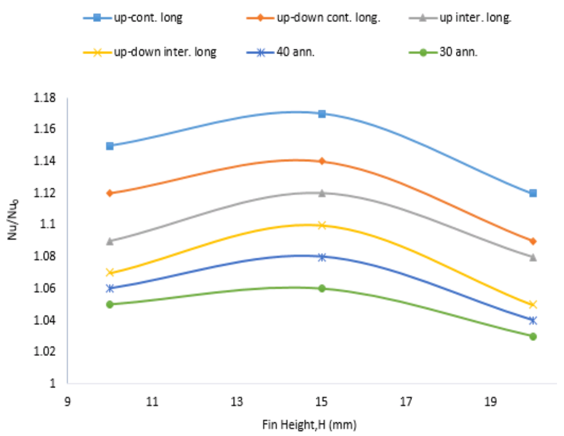

Figure 4. Average Nusselt number of finned tube relative to the finless tube with convergent parabolic shaped fins

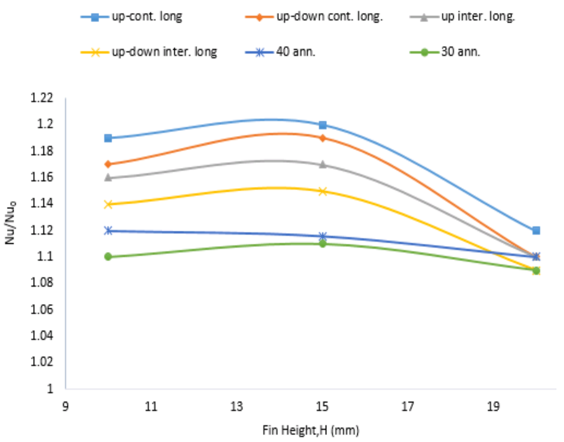

Figure 5. Average Nusselt number of finned tube relative to the finless tube with divergent parabolic shaped fins

The thermal enhancement factor is a parameter that considers changes in heat transfer and flows properties simultaneously. When it comes to choosing the optimal temperature for maximum heat transfer and the lowest coefficient of friction, it is essential to determine the thermal enhancement factor. Because, the executive and economic justification of the optimal state is conditional on having $\eta > 1$ [27].

$$\eta = \frac{\dfrac{Nu}{Nu_0}}{(\dfrac{f}{f_0})^{1/3}} \tag{3}$$

In Equation (3), Nu_0 and $f_0$are the Nusselt number and the coefficient of friction of the reference state without Fin, respectively. Also, Nu and f are the Nusselt number and the coefficient of friction of the tube with Fin, respectively. Figures 11-13 demonstrate the thermal enhancement factor for different types and profiles of fins. The highest parameter of thermal enhancement factor is related to the divergent parabolic profile, which,

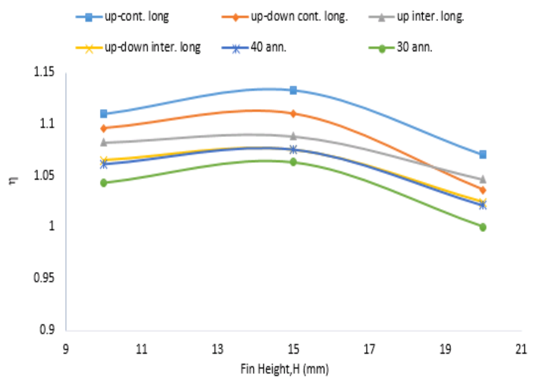

Figure 11. The thermal enhancement factor with rectangular shaped fins

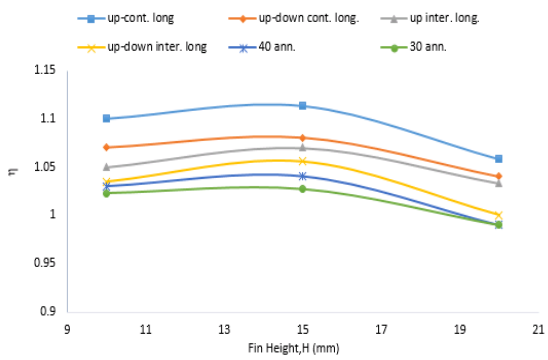

Figure 12. The thermal enhancement factor with convergent parabolic shaped fins

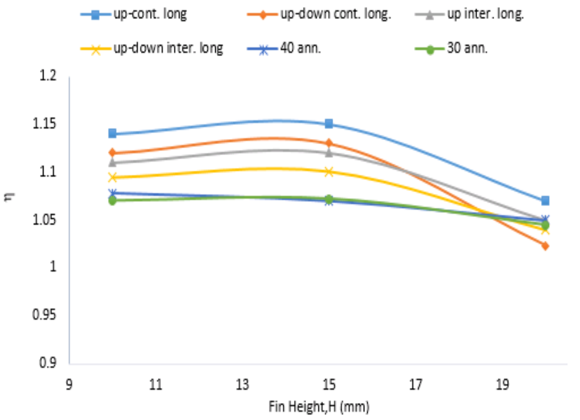

Figure 13. The thermal enhancement factor with divergent parabolic shaped fins

despite the high-pressure drop, an increase in heat transfer coefficient leads to the maximum thermal enhancement factor. In the convergent parabolic section, the thermal enhancement factor for circular fins with an H = 20 mm height is less than one. The rest of the cases show that improving the heat transfer coefficient overcomes the increase in the coefficient of friction, and the application of fins from the optimization point of view is justified.

4. CONCLUSION

In pressure reduction stations, before the constant enthalpy process of pressure failure, the indirect water bath heater preheats the natural gas to prevent phase change and gas hydrate formation. This paper studies the feasibility of applying fins along tubes to increase the transferred heat to the natural gas and increase thermal efficiency. Two longitudinal and circular fins are selected according to the condition of the tube. Three different profiles for fins are considered in the simulations. The flow was considered three-dimensional, incompressible, and steady. For simulation and analysis, a first-order characteristics-based scheme is used to obtain convective fluxes, and the second-order averaging method is used to calculate the viscous fluxes in the numerical method. The fifth-order Runge-Kutta method is applied for time marching. FORTRAN was also utilized to solve the governing equations. The Rayleigh number lies within the beginning of the transition range $(10^9 - 10^{11})$. Experimental results of similar articles were used to validate the numerical results in this paper.

The results show that for the dimensionless heat transfer coefficient, due to the use of the fin, compared to the finless case, for three sections, including rectangular, convergent parabolic, and divergent parabolic, it increases by 3 to 20%. Also, the dimensionless heat transfer coefficient increases from 8 to 18% due to using solid fins, from 7 to 16% due to the use of interrupted fins, and from 10 to17%, and 8 to 15% due to the use of 4 and 2 blades, respectively. Increasing the ratio of fin height to tube diameter, the presence of the fin, acts the role of heat trap and prevents the flow motion. Hence, H/D has the most significant improvement on heat transfer, and with increasing Rayleigh number, its effect also increases. Among the three cases selected for fin height, H=15 mm has the highest Nusselt increase. The highest heat recovery parameter is related to the divergent parabolic cross-section. Despite the high-pressure drop, increasing the heat transfer coefficient leads to the maximum heat recovery parameter. It shows that the improvement of the heat transfer coefficient overcomes the increase of the coefficient of friction, and the application of the fin is justified from the optimization point of view.

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Persian Abstract

چکیده

برای جلوگیری از تغییر فاز و تشکیل هیدرات گازی در ایستگاههای کاهش فشار باید گاز طبیعی را از پیش‌گرم کرد. این مقاله با هدف بررسی تأثیر وجود پره روی لوله‌های گاز و پیکربندی آن، چینش و شکل آنها بر انتقال حرارت به گاز و بازده حرارتی انجام می‌گردد. برای آنالیز حساسیت، دو مورد لوله با پره و بدون پره، و برای چینش پره‌ها، دو ترتیب طولی و دایره‌ای، و برای پیکربندی پره‌ها، دو حالت پیوسته و منقطع مورد تحلیل قرار گرفت. همچنین، سه نوع سطح مقطع مستطیلی، سهموی همگرا و سهموی واگرا برای شکل پره‌ها مورد مطالعه قرار گرفته است. برای شبیه سازی، جریان به صورت سه بعدی، تراکم ناپذیر و پایدار در نظر گرفته شد و برای تحلیل عددی و گسسته‌سازی معادلات گرمای همرفت، از روش مشخصه‌محور استفاده شد. برای پیاده‌سازی و حل معادلات با کدنویسی از نرم افزار FORTRAN استفاده شد. نتایج نشان می‌دهند که در حالت پره‌های پیوسته و منقطع، با افزایش تعداد پره‌ها، ضریب انتقال حرارت بی‌بعد افزایش می‌یابد و با افزایش نسبت ارتفاع پره به قطر لوله، ضریب انتقال حرارت کاهش می‌یابد. همچنین، بیشترین بهبود انتقال حرارت مربوط به سطح مقطع پره سهمی واگرا بود.