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Performance Analysis in Study of Heat Transfer Enhancement in Sinusoidal Pipes

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In this study, a performance analysis of the sinusoidal pipes with various amplitudes (in constant period) and various periods (in constant amplitude) have been performed by utilizing non-dimensional entropy generation equation (*Ns*) mathematically developed for constant wall temperature thermal boundary condition. According to the performance analysis based upon the characteristics obtained in experimental study; for laminar flow 2Sin 0.25*X* pipe shows the best performance in constant period while Sin 0.5*X* and Sin *X* pipes show the best performance in constant amplitude. For turbulent flow the all-sinusoidal pipes show nearly the same performance as the straight pipe in constant period while Sin 0.25*X* and Sin 0.5*X* pipes show the best performance in constant amplitude.

Analiza performansi pri studiranju poboljšanog prijenosa topline u sinusoidalnim cijevima

Izvornoznanstveni članak

U ovoj je studiji dana analiza performansi sinusoidalnih cijevi s promjenljivim amplitudama (uz konstantni period) i s varijabilnim periodima (uz konstantnu amplitudu) koristeći bezdimenzijsku značajku entropijske generacije (*Ns*), koja je razvijena uz rubni uvjet konstantne temperature stijenke. Pozivajući se na analizu performansi koje su bazirane na karakteristikama dobivenim eksperimentima, može se zaključiti: za laminarno strujanje najbolje performance pokazuje cijev 2 Sin(0.25*X*) u konstantnom periodu, dok cijevi oblika Sin(0.5*X*) i Sin(*X*) pokazuju najbolje performance pri konstantnoj amplitudi. Pri turbulentnom strujanju sve sinusoidalne cijevi, s konstantnim periodom, pokazuju najbolje približno iste performance kao ravna cijev, dok cijevi oblika Sin(0.25*X*) i Sin(*X*) pokazuju najbolje performance pri konstantnom periodu

1. Introduction

Methods for performance evaluation of the heat transfer enhancement devices are presented in the literature (Campbell 1999, Kakaç et al. 1987, Rohsenow et al. 1985, Sparrow and Comb 1983, Lee et al. 1985). The aim of most of these methods is to evaluate the parameters among themselves such as pressure loss, flow rate and pumping power which are taken as main characteristics. Next, in the case of one of the parameters mentioned as constant, changes in heat transfer and other parameters reveal the performance of enhancement methods. With this analysis, the appearance of multiple performance criteria causes difficulties in identifying a definite result in enhancement technique for comparison. For an optimal solution, characteristics obtained in result of calculations can be re-evaluated among themselves. Despite all these, Bejan (1997) proposed the evaluation method based on the second law of thermodynamics. In this method, irreversibility and entropy generation are used as performance evaluation criteria in the system to which enhancement technique is applied. Entropy generation in convective heat transfer process, arises from fluid-flow friction and heat transfer occurring in finite temperature difference. Consequently, minimization of the entropy generation yields the criterion for system optimization.

Meanwhile performance analysis by considering the entropy generation can be performed with exergy analysis. At this point, the exergy destruction can be determined by using the exergy analysis. As this destruction is equal to the entropy generation, a different approach to performance analysis has been done. Prasad and Shen (1993), in their study, evaluated the performance of heat transfer enhancement devices by using exergy analysis. The difference of this method from Bejans (1997) is that the effect of axial temperature variation in the passage transferring heat is also taken into consideration. In the study, an exergy analysis was made by taking into consideration the fact that the effect of pressure loss in pipe heat exchangers for liquid (water in this study) to

Symbols/Oznake

L	- length of the pipe, m duljina cijevi
D	- inner diameter of the pipe, m - unutrašnji promjer cijevi
T_w	- pipe wall temperature, °C - temperatura stijenke cijevi
T_{fi}	- inlet temperature of the fluid, °C - ulazna temperatura fluida
T_{fo}	- outlet temperature of the fluid, °C - izlazna temperatura fluida
ΔP	- static pressure difference, N/m^2 - razlika statičkog tlaka
Re	- Reynolds number - Reynoldsov broj
Pr	- Prandtl number - Prandtlov broj
Ns	- non-dimensional entropy generation - bezdimenzijska entropijska produkcija
c_{pm}	- average specific heat capacity at constant pressure of the fluid, kJ/(kg · K) - specifični toplinski kapacitet fluida pri konstantnom tlaku
k_m	- thermal conductivity of the fluid W/(m · K) - toplinska provodnost
h_m	- average heat transfer coefficient, W/(m^2 · K) - prosječni koeficijent prijenosa topline
U_m	- average velocity of the fluid, m/s - prosječna brzina strujanja fluida
$\dot{m}$	- mass flow rate of the fluid, kg/s - maseni protok fluida
f	- friction factor - faktor trenja
ρ	- density of the fluid, kg/m^3 - gustoća fluida
τ	- non-dimensional inlet temperature difference - bezdimenzijska ulazna temperaturna razlika
v	- kinematic viscosity, m^2/s - kinematička žilavost

Indices/Indeksi

m	- average - prosječni
w	- wall - stijenka
fi	- fluid inlet - ulazni fluid
fo	- fluid outlet - izlazni fluid

enthalpy change is small and this can be neglected. As a result of this, in the study mentioned the expression of exergy destruction is valid only in pipe heat exchangers in which liquid is used as a fluid.

In this present study, a performance analysis of sinusoidal pipes with various amplitudes (in constant period) and various periods (in constant amplitude) was carried out by utilizing the non-dimensional entropy generation equation (Ns) mathematically developed for constant wall temperature thermal boundary condition in heating application, as suggested by Nag and Mukherjee (1987). The heat transfer and fluid-flow friction characteristics which are necessary for the analysis were obtained experimentally. The pipe configuration is characterized by the amplitudes and periods of the Sine function, the respective expression of which are Sin 0.25X, 2Sin 0.25X and 4Sin 0.25X, which are called sinusoidal pipes in constant period, and Sin 0.25X, Sin 0.5X, Sin X and Sin 2X, which are called sinusoidal pipe in constant amplitude. The sinusoidal pipes were curved without decreasing in the cross-section along the axis of the pipe. Experiments were performed for both laminar and turbulent flow conditions in the Reynolds number range from 75 to 23000 and air was used as working fluid. The test pipes were 812 mm long and 4 mm inner diameter. Comparative studies of heat transfer and fluid-flow friction results of the sinusoidal pipes were given by [1-3] for laminar and turbulent flows respectively.

In addition, in order to estimate unavoidable errors in experimental results, an uncertainty analysis was performed as well, which is appropriate for the literature [1, 6, 12].

2. Theoretical Study

2.1. Test setup

This study is a theoretical study using data which have been obtained experimentally. The experiments were performed in sinusoidal pipes with various amplitudes and various periods for hidrodynamically fully developed, thermally developing and fully developed laminar and turbulent flows.

The schematic drawing of experimental setup is shown in Figure 1. The pipe configuration is characterized by the amplitude and period of the Sine function. The respective expressions are Sin 0.25X, 2Sin 0.25X and 4Sin 0.25X

for constant periods and Sin 0.25*X*, Sin 0.5*X* and Sin *X* for constant amplitudes. The test pipes were 812 mm in length and 4 mm in inner diameter. All pipes were made of copper, resulting in small conductive resistance in the pipe wall. For constant periods of sinusoidal pipes, the entire pipe encompassed one corrugated cycle. For constant amplitude experiments, the pipes encompassed 1, 2, 3.5 and 5 cycles respectively. All the schematic drawings of the test pipes including straight pipe are shown in Figure 2.

Experiments were performed under constant wall temperature boundary condition. A constant temperature bath was constructed in dimensions of 1050×300×350 mm. The bath was made of Plexiglas, which has very much lower thermal conductivity than the metallic wall, to minimize the heat loss of surroundings. Constant wall temperature was accomplished by sending saturated steam at atmospheric pressure to the test section, where this saturated steam was condensed on the surface of sinusoidal test pipes.

By this method, 100±1 °C constant wall temperature boundary condition was sustained. This boundary condition was continuously checked by measuring surface temperature at 12 different locations on the test pipes. These temperature measurements were performed by using copper-constant thermocouples attached to pipes with 65 mm intervals. These thermocouples were placed in holes drilled from the rear face of the pipe. All thermocouples were made from 0.127 mm diameter teflon-coated copper and constantan wire that had been specifically calibrated for the present experiments. In addition, the equipment used in experiments includes a compressor, a manometer for pressure difference measurements between inlet and outlet, two thermocouples for inlet and outlet air temperature measurements, a calibrated rotameter for mass flow rate measurement, a steam generator unit, test section etc.

The sinusoidal pipe was connected to the compressor from which air was supplied to the system. An inlet pipe was used in the system between compressor and test pipe to provide for fully developed turbulent flow. First, the straight pipe measurements were performed for different Reynolds numbers and the correctness of these results was verified by comparing them with literature. Then, two different groups of tests were performed. The first group was called constant period experiments in which the pipe was bent as a Sine function that has constant amplitude but different periods. The second group was called constant period experiments in which the period was fixed and amplitude was varied.

2.2. Performance Analysis

As stated above, in this study, performance analysis of sinusoidal pipes with various amplitude (in constant period) and various periods (in constant amplitude) was carried out by utilizing the non-dimensional entropy generation equation (*Ns*) mathematically developed for constant wall temperature thermal boundary condition in heating application, as suggested by [9]. The equation developed for this purpose in this study is as follows:

$$Ns = \left[\tau \left[\exp(-\gamma L) - 1 \right] + \ln \left[\frac{\left[\tau \exp(-\gamma L) - 1 \right]}{(\tau - 1)} \right] \right] + \frac{1}{\rho\, T_w \gamma\, c_{pm}} \left(-\frac{\mathrm{d}P}{\mathrm{d}x}\right) \ln \left[\frac{\left[\tau \exp(-\gamma L) - 1 \right]}{(\tau - 1) \exp(-\gamma L)} \right], \tag{1}$$

where τ is expressed as dimensionless inlet temperature difference and given by

$$\tau = \frac{T_w - T_{fi}}{T_w}, \tag{2}$$

where T_w is the wall or surface temperature of the pipe and T_{fi} is the inlet temperature of the working fluid. In Equation 1, the value of the γ was calculated as follows

$$\gamma = \frac{h_m\, \pi\, D}{\dot{m}\, c_{pm}}, \tag{3}$$

where h_m is the average heat transfer coefficient, D is the inner diameter of the pipe, $\dot{m}$ is the mass flow rate of working fluid, which is air in this study and c_{pm} is the average specific heat of working fluid. At the same time, in Equation 1, the pressure gradient was calculated as follows

$$\left(-\frac{\mathrm{d}P}{\mathrm{d}x}\right) = \frac{f\, \rho\, U_m^2}{2\, D}, \tag{4}$$

where f is the friction factor, U_m is the average velocity of the working fluid and ρ is the density of working fluid. Besides, in Equation, L is the length of the pipe.

In Equation 3 and 4, the variables of h_m, f and U_m were calculated with the help of the following equations:

$$h_m = \frac{\dot{m} c_{pm}}{\pi\, DL} \ln \left(\frac{T_w - T_{fi}}{T_w - T_{fo}} \right), \tag{5}$$

$$f = \frac{\left(\frac{\Delta P}{L} \right) D}{\rho\, U_m^2 / 2}. \tag{6}$$

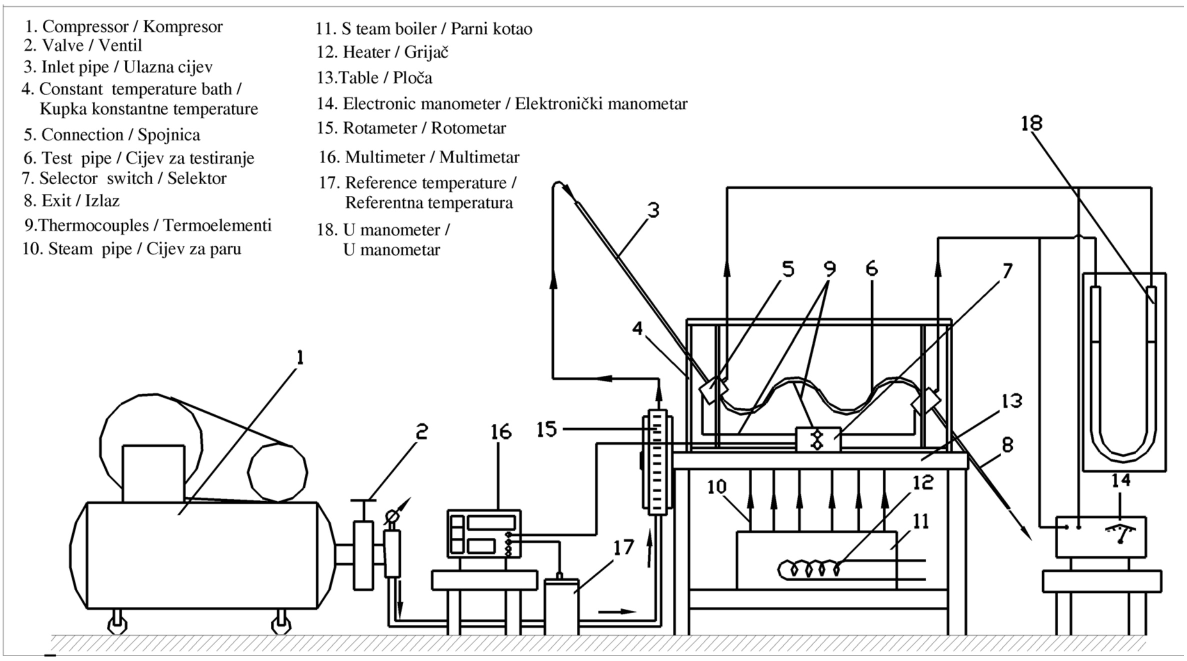


Figure 1. Schematic drawing of the experimental setup

Slika 1. Shematski prika eksperimentalnog uređaja

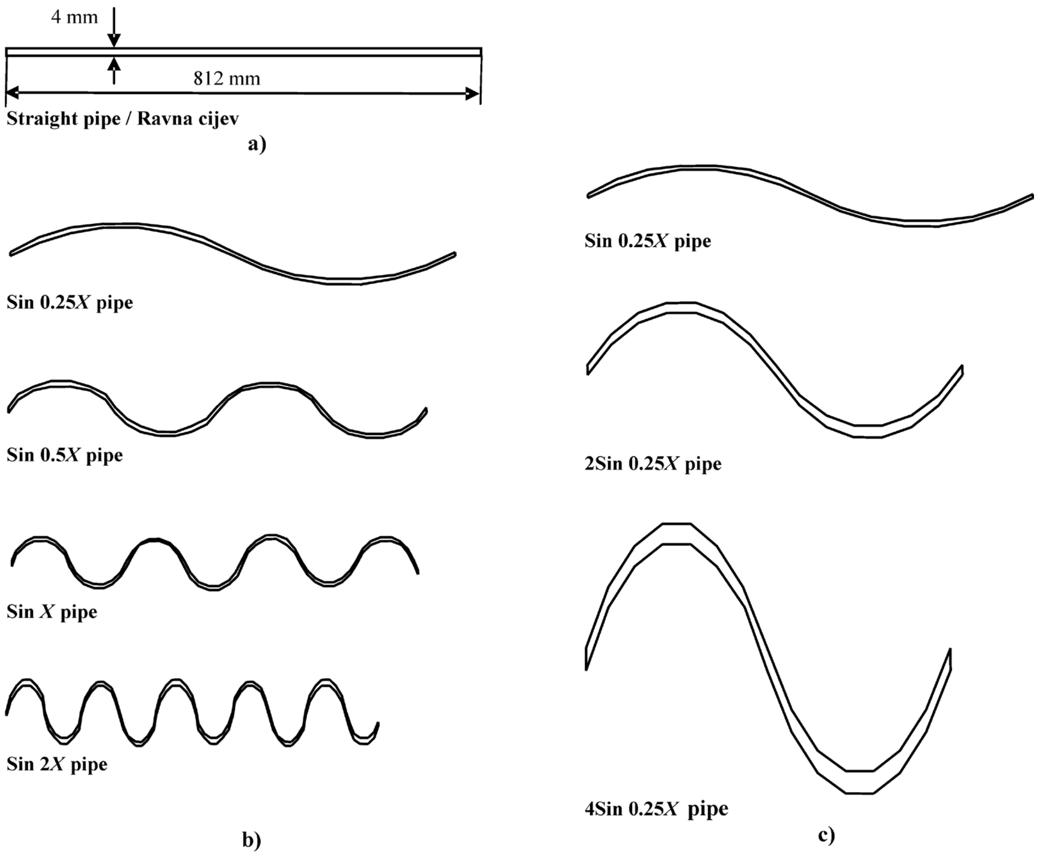


Figure 2. Schematic drawing of the sinusoidal pipes: a) Straight pipe, b) Sinusoidal pipes with various periods (in constant amplitude), c) Sinusoidal pipes with various amplitudes (in constant period)

Slika 2. Shematski crtež sinusoidalnih cijevi: a) Ravna cijev, b) Sinusoidalne cijevi s varijabilnim periodima (s konstantnim amplitudama), c) Sinusoidalne cijevi s varijabilnim amplitudama (s konstatnim periodom)

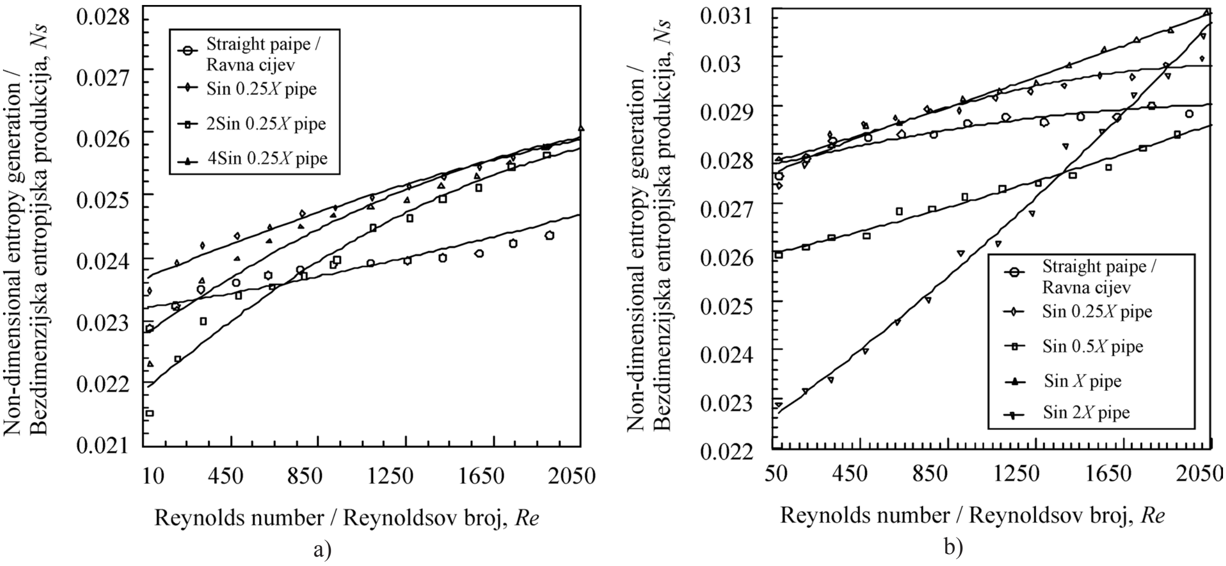


Figure 3. Variation of non-dimensional entropy generation with Reynolds number for laminer flow: a) Sinusoidal pipes with various amplitudes (in constant period), b) Sinusoidal pipes with various periods (in constant amplitude)

Slika 3. Utjecaj Reynoldsovva broja na bedimenzijsku generaciju pri laminarnom strujanju: a) Sinusoidalne cijevi s promjenljivim amplitudama (uz konstantni period), b) Sinusoidalne cijevi s promjenljivim periodima (uz konstantnu amplitudu)

$$U_{\mathrm{m}} = \frac{4\,\dot{m}}{\rho\,\pi\,D^2}. \qquad (7)$$

In Equation 5, T_{fo} is the outlet temperature of the working fluid. In Equation 6, ΔP is the static pressure difference between the inlet and outlet of the working fluid passing through the pipe.

2.3. Uncertainty Analysis

Using conventional techniques, the uncertainties for all of the experimental values measured were estimated. The thermocouples used in the heat transfer section are calibrated individually, and the maximum error is estimated to be ±0.5 °C. The rotameters have been calibrated and the error is less than ±1%. Other errors were also included in the analysis to estimate overall uncertainty appeared during the mass flow rate measurements. Corrections were also made to allow for changes in temperature and pressure during the tests. The manometer has been calibrated to give a maximum error of less than ±2%. An important contribution to the pressure drop uncertainty is the error due to air leakage in the test section. Likely, other errors in pressure drop measurements were included in the analysis to estimate overall uncertainty. Besides, the geometric quantities of the pipes, length and inner diameter, were determined within ±5 mm and ±0.1 mm respectively.

Table 1. The experimental uncertainties in this study.

Tablica 1. Eksperimentalne nesigurnosti u ovoj studiji

Variables / Varijable	Uncertainty / Nesigurnost (%)
Air inlet temperature / Ulazna temperature zraka	±1.5
Air outlet temperature / Izlazna temperature zraka	±3.5
Pipe wall temperature / Temperature cijevi	±1.5
Pressure drop / Pad tlaka	±3.5
Mass flow rate / Maseni protok	±3.5
Reynolds number / Reynoldsov broj	±4
Nusselt number / Nusseltov broj	±18
Friction factor / Faktor trenja	±10

Finally, a root-sum-square combination of the effects of each of individual sources of error yields estimates of the uncertainties as shown in Table 1. Measurements were shown to be reproducible well within these limits.

3. Results and discussion

In this study, a performance analysis was carried out by calculating the values of non-dimensional entropy generation utilizing Equation 1 mathematically developed for a constant wall temperature thermal boundary condition in heating application. The values of non-dimensional entropy generation obtained from the experimental data for sinusoidal pipes in constant period and in constant amplitude are shown in Figures 3 and 4 for laminar and turbulent flows respectively. At this point, the values of non-dimensional entropy generation for each pipe, including straight pipe, were determined by considering the second law of thermodynamics. Comparing the straight pipe, sinusoidal pipe in which the non-dimensional entropy generation is minimum will be the best (optimum) pipe enhancing (augmenting) heat transfer. In other words, comparing the straight pipe, sinusoidal pipe in which the non-dimensional entropy generation is minimum, will be the pipe having the highest performance.

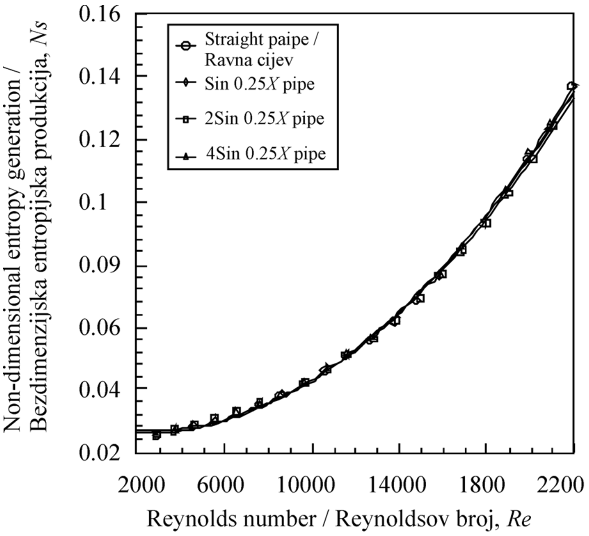
The values of non-dimensional entropy generation obtained for the sinusoidal pipes with constant amplitude and constant period in laminar flow are given in Figure 3. For constant period, 2Sin 0.25*X* pipe shows the minimum values of non-dimensional entropy generation by approximately Re = 700 while the minimum non-dimensional entropy generation occurs in straight pipe after this point. At approximately Re = 2000, all sinusoidal pipes with constant amplitude show similar values of non-dimensional entropy generation. Although minimum non-dimensional entropy generation is expected to be in a straight pipe, 2Sin 0.25*X* pipe is the one by approximately Re = 700, in which minimum non-dimensional entropy generation occurs. In constant amplitude, Sin 2*X* pipe shows the minimum non-dimensional entropy generation by approximately Re=1300 while the maximum value of the non-dimensional entropy generation is reached in this pipe above approximately Re=1300. After Re=1300, Sin 0.5*X* pipe shows the minimum non-dimensional entropy generation.

The value of non-dimensional entropy generation determined in sinusoidal pipes with constant period and constant amplitude for turbulent flow are given in Figure 4. As shown in Figure 4a, very closed values of non-dimensional entropy generation appear for the constant period. As shown in Figure 4b, in sinusoidal pipes with constant amplitude, the maximum non-dimensional entropy generation takes place in Sin 2*X* pipe. However, the minimum non-dimensional entropy generation occurs in Sin 0.25*X* pipe after the straight pipe. Besides, another pipe showing very closed value of non-dimensional entropy generation to Sin 0.25*X* pipe is Sin 0.5*X* pipe.

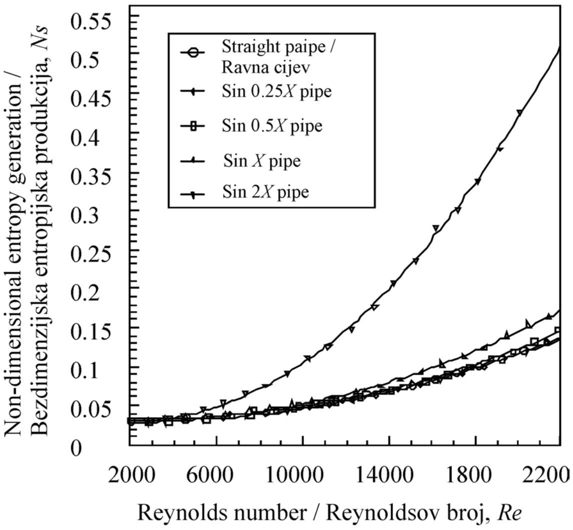
According to results of uncertainty analysis performed to determine the accuracy of experimental results, in which unavoidable measurement errors are estimated, it is concluded that the maximum uncertainty values can result from errors in measurements of mass flow rate, air outlet temperature and pressure drop. The attention in measurements of mass flow rate, air outlet temperature and pressure drop will decrease considerably. In this study, the results of uncertainty analysis agree with the literature [12].

4. Conclusions

In this study, performance analysis of the sinusoidal pipes with various amplitude (in constant period) and various periods (in constant amplitude) was carried out by utilizing the non-dimensional entropy generation equation (Ns) mathematically developed for constant wall temperature thermal boundary condition in heating application. In the performance analysis carried out with characteristics obtained from the experiments, 2Sin 0.25*X* pipe shows the best performance in constant period while



a)



b)

Figure 4. Variation of non-dimensional entropy generation with Reynolds number for turbulent flow: a) Sinusoidal pipes with various amplitudes (in constant period); b) Sinusoidal pipes with various periods (in constant amplitude)

Slika 4. Utjecaj Reynoldsovva broja na bedimenzijsku generaciju pri turbulentnom strujanju: a) Sinusoidalne cijevi s promjenljivim amplitudama (uz konstantni period); b) Sinusoidalne cijevi s promjenljivim periodima (uz konstantnu amplitudu)

Sin 0.5X and Sin 2X pipes show the best performance in constant amplitude for laminer flow. All sinusoidal pipes show almost the same performance as a straight pipe while Sin 0.25X and Sin 0.5X pipes show the best performance in constant amplitude for turbulent flow.

Sinusoidal pipes, except for Sin 2X pipe, can be used in the heat transfer enhancement application without extra pumping power. For this purpose, the sinusoidal pipes can be used in solar collectors, refrigeration equipment and heat exchangers, in which heat transfer is needed to augment. Although some difficulties in serial manufacturing of sinusoidal pipes are present, it is possible to overcome these restrictions thanks to new developing technologies.

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