A NEW HEAT TRANSFER CORRELATION FOR OSCILLATING FLUID FLOW

Mehmet Turgay PAMUK
Piri Reis University, Tuzla, 34940 Istanbul,Turkey
turgaypamuk@hotmail.com

Abstract

In this study, heat transfer under oscillating flow conditions has been investigated conducting a wide range of experiments using water as the flow medium. Experimental data have been reduced to obtain relevant heat transfer parameters, namely Nusselt number, and compared to those obtained by the previous researchers. The new correlation obtained herein covers a wide range of flow conditions and it takes into account the effect of Prandtl number which is very sensitive to temperature variations, thus it is believed to be a good representation of the physical problem. A total of 27 sets of heat transfer experiments, each representing a different frequency, flow displacement length and heat input, have been conducted. Heat applied is absorbed by concentric-pipe heat exchanger where calculations have been performed.

Key words : *Oscillating Flow, heat transfer*

1. Introduction

Heat transfer in oscillating flow has been a fundamental investigation field studied over the past few decades. Oscillating flow is a physical phenomenon encountered in internal combustion engines, Stirling engines, cryogenic coolers, chemical processes and medical sciences. It has many important applications in the compact heat exchangers, cooling processes of nuclear plants, design of Stirling heat engines and heat transport in internal combustion machines.

Oscillating flows can be either pulsating where flow oscillates around a non-zero average or reciprocating where flow changes its direction at every half cycle, thus the average velocity in reciprocating flow is zero. Pulsating flow has been studied extensively in medical and biological sciences. This type of fluid flow can also be observed at the outlet of a piston pump, suction and exhaust manifolds of internal combustion engines, hydraulic and pneumatic lines and control systems or as pulsating blood flow through the veins. On the other hand, reciprocating flows can be observed in many applications such as internal combustion engines, Stirling engines and cryogenic coolers or air motion in and out of lungs.

The fact that oscillating flow has two thermal entrance regions is one of the reasons why it enhances heat transfer. There are a number of empirical correlations available for hydrodynamic and thermal calculations, however the phenomenon has not yet been fully understood due to the scarcity of experimental data and difficulty in mathematical modeling. In the past studies, the effect of oscillation on the heat transfer enhancement was investigated analytically and experimentally. These studies include self and forced oscillation.

Akdag et al. [1] have shown that the heat transfer in an oscillating vertical fluid column can be mathematically modelled using the control volume approach by obtaining simplified mass, momentum and energy conservation equations and solving them by Runge-Kutta method. Comparison of their theoretical results with experimental data is shown to be in good agreement.

Ozdemir and Ozguc [2] have used a mathematical model, where the hydrodynamics and thermodynamics of a Fluidyne heat machine having three columns are analyzed systematically. They have shown that the heat added and absorbed in Fluidyne heat engine must be equal in order for the system to be stable (except friction).

Akdag ve Ozdemir [3] have investigated experimentally the heat transfer from a surface heated with constant heat flux to an oscillating vertical annular liquid column having an interface with the atmosphere. Based on the experimental data a correlation equation has been obtained for the cycle-averaged Nusselt number as a function of kinetic Reynolds number.

Arslan ve Ozdemir [4] have investigated experimentally the heat transfer in an oscillating loop heat pipe. They have shown that the system consisting of an oscillating heat pipe made up of three interconnected fluid columns has two degrees of freedom and the second frequency is double the first one and the overall heat transfer coefficient based on the temperature difference between the evaporator and condenser surfaces is introduced by a correlation function of dimensionless numbers such as kinetic Reynolds number and other parameters.

Akdag *et al.* [5] have studied experimentally the heat removal from a surface, which is located into the reciprocating flow in a vertical annular liquid column. They have obtained a correlation regarding heat absorption from a vertical annular fluid column using the control volume approach and shown that the Nusselt number increases with increasing frequency where cycle-averaged values are considered in the calculation of heat transfer using the experimental measurements.

Zhao and Cheng [6] have conducted heat transfer experiments for sinusoidal flow in a finite-length pipe and have shown that the heat transfer can be characterized with kinetic Reynolds number, non-dimensional oscillating fluid displacement, length/diameter ratio of pipe and the Prandtl number.

Shahin [7] has shown that in an annular oscillating flow between two concentric pipes, Nusselt number increases with increasing frequency up to a certain value.

Walther *et al.* [8] have investigated the heat transfer associated with turbulent oscillating flow conditions as found in heat exchangers of regenerative thermal machines based on numerical flow modelling and a suitable low-Reynolds number k-ε turbulence model.

Zhao and Cheng [9] have carried out an experimental study for laminar oscillatory forced convection in a long circular tube heated by uniform heat flux and subjected to a laminar reciprocating flow of air. The numerical solutions for time-resolved centerline fluid temperature, cycle-averaged wall temperature, and the space-cycle averaged Nusselt number are shown to be in good agreement with the experimental data. Based on the experimental data, a correlation equation for the space-cycle averaged Nusselt number of an oscillatory laminar flow of air in a long tube in terms of appropriate similarity parameters is obtained.

Bouvier *et al.* [10] have built an instrumented test rig which allowed them to study heat transfer in oscillating flow. They have shown that fundamental frequencies are not the same in the wall and in the fluid.

Akdag and Ozguc [11] have studied the heat transfer from a surface having constant heat flux subjected to oscillating flow in a vertical annular liquid column. The experiments have been carried out for four different oscillation frequencies, three amplitudes and three heat fluxes while the other parameters remain constant. The cycle-averaged values have been considered in the calculation of heat transfer using the control volume approximation. Comparison of their theoretical results with experimental data is shown to be in good agreement.

Gul [12] has examined experimentally the heat transfer characteristics of oscillating turbulent air flow in a circular pipe heated at uniform heat flux. Results have shown that Nu is strongly affected by the oscillating frequency and Reynolds number. The variation is more pronounced in the entrance region than in the downstream fully developed region.

Zhibin *et al.* [13] have investigated the mechanism of the heat transfer associated with the oscillatory flow in detail. The phase lag between different layers of gas adjacent to the wall leads to large transverse temperature gradient normal to the plate surface, which gives rise to the temperature undershoot and overshoot phenomena. These time dependent transverse temperature gradients enhance the heat transfer between the gas and plates, as well as the heat transfer along the channel.

In this experimental and analytical study, it is aimed to obtain a heat transfer correlation to be used in heat transfer calculations in oscillating flow and compare this new correlation with those of other researches. The new correlation is considered to be a good representation of the physical phenomenon owing to the fact that it takes into account the effect of Prandtl number which considerably changes with temperature variations.

2. Experimental Test Rig

A schematic diagram of the experimental test rig is shown in fig. 1. It is made up of a heated section where heat is applied circumferentially at various levels, a double acting piston-cylinder assembly made from stainless steel used as oscillation generator and two concentric heat exchangers installed symmetrically which are also made from stainless steel. Oscillation is obtained using a flywheel-crank assembly that is driven by a reducer motor. The rotational speed is changed by means of an A/C motor drive that converts the line frequency of 50 Hz to a desired value. Frequencies of 5, 10 and 15 Hz have been used in this work that correspond to piston frequencies of 0.116 Hz, 2.330 Hz and 3.495 Hz, respectively. Two constant temperature bathes (C.T.B.) with circulation pumps, each having a maximum cooling capacity of 300W, are connected to the heat exchangers provide cooling water and share the heat load equally.

Three thermocouples, T_{in}, T_{w1} and T_{w2} are installed at the heat exchangers' oscillating water inlets and the cooling water inlet and outlets, as shown in the figure. Temperature data have been collected using a Keithley 2700 data acquisition system and a computer analyzes the collected data. All thermocouples are K-type (Ni-Cr/Ni-Al). Temperature data collected have been time averaged over the number of cycles each set of experiment was conducted.

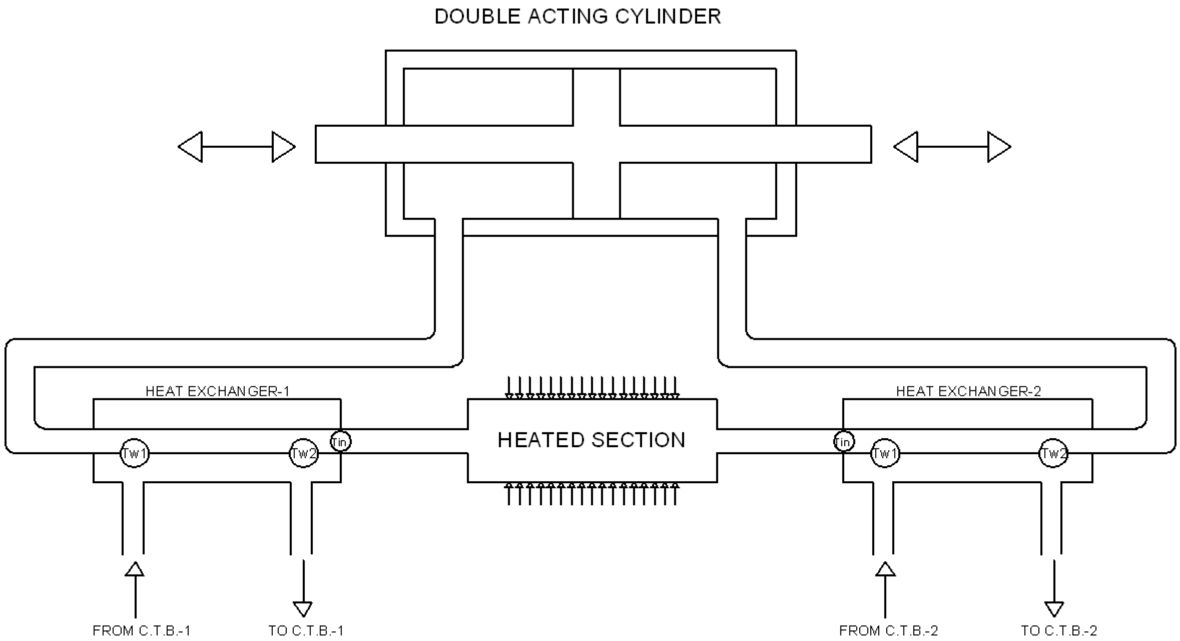

Figure 1 : Experimental test rig for oscillating flow

3. Uncertainty Analysis

Uncertainty in the experimental data is considered by identifying the main sources of errors in the primary measurements such as power supplied, temperature, time and frequency. Then, an uncertainty analysis based on the method described by Figliola and Beasley [14] has been performed. The uncertainties of dimensions, power, temperature, and Nusselt numbers are estimated to be 0.31%, 0.66%, 0.67%, and 2.39% respectively.

4. Results and Discussion

Heat transfer experiments for estimating the Nusselt number in oscillating flow have been conducted at three different power inputs q, by selecting three different piston strokes, x_{pmax} and three different frequency outputs of A/C drive, n. This way 27 sets of experiments have been conducted. Rotational speed of reducer motor at 50 Hz line frequency is nominally 70 rpm. Thus rotational speed and corresponding frequency are calculated by $N=(70/50)n$ and $f=N/60$ respectively for a given drive frequency, n. Angular frequency is $\omega=2pf$. Actual rotational speed of the reducer motor determined is to be 69.9 rpm using *Fast Fourier Transform* at Matlab© software. The displacement of the piston has been taken as zero at the rear position inside the cylinder and it becomes a maximum which is equal to the diameter of the flywheel at the forward position. The piston displacement is equal to the fluid displacement due to the fact that the fluid is incompressible, as water has been used as flow medium. Hence, at the entrance of the heat exchangers where heat transfer calculations have been made, the fluid displacement x_m varies according to eq. (1):

$$x_m(t) = \frac{X_{max}}{2}(1 - \mathrm{Cos}\omega t) \tag{1}$$

where $x_{max}=x_{pmax}A_p/A=2RA_p/A$ and, R, A_p and A are flywheel radius, cross sectional areas of double acting cylinder and inner pipe of heat exchanger, respectively. The cross-sectional mean fluid velocity in the pipe is $u_m(t)=u_{max}Sin\omega t$ where $u_{max}=\omega x_{max}/2$.

Time averaging for temperature data has been made for 60 cycles. Temperature variation at the heat exchanger inlet has been assumed to be sinusoidal in the form $T(t)=T_m+T_{max}Sin\omega t$ where T_m is the time average of the temperature and T_{max} is the amplitude of the temperature variation. The assumption has been verified by comparing the results of this assumption with the experimental data (fig. 2). This is the test run for 130 mm stroke length, 300 W power input and 10 Hz line frequency.

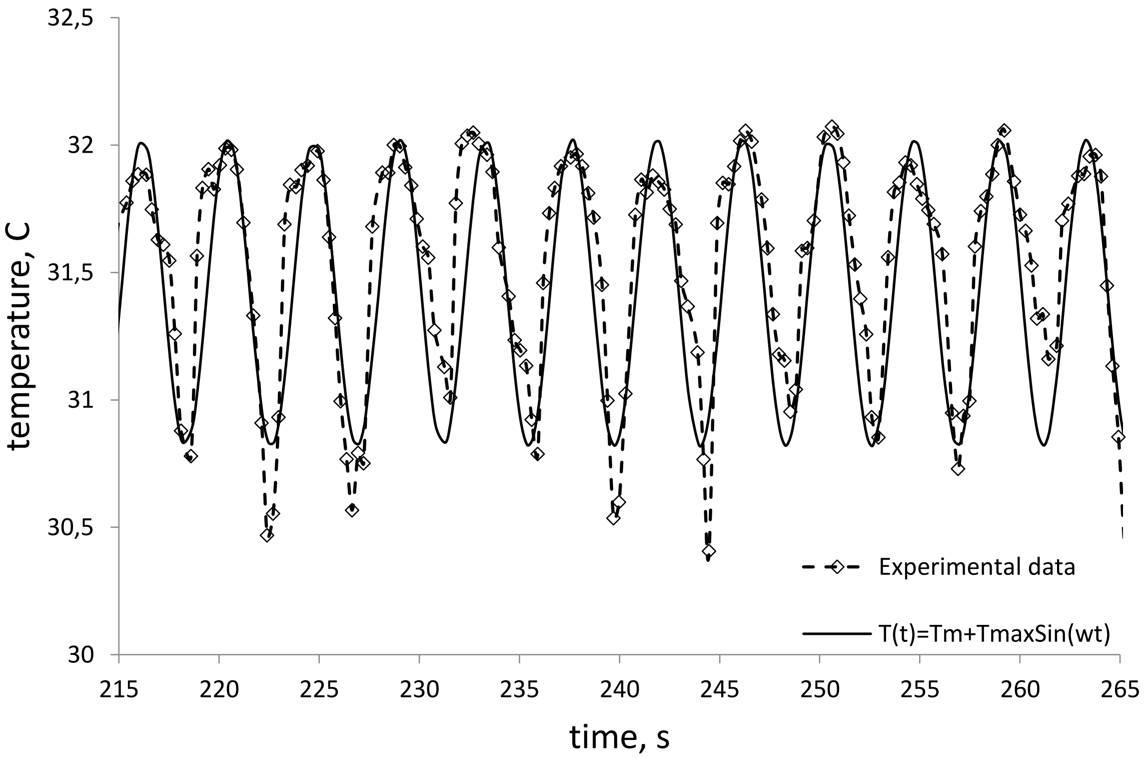

Figure 2 : Variation of temperature of oscillating fluid at the heat exchanger inlet.

Heat balance calculations for heat exchangers have been performed as shown in tab. 1. Temperature difference at the inlet and outlet and the flowrate of cooling water supplied by the constant temperature bathes, have been used to perform the calculations in the form $Q_{absorbed}=mC_p\Delta T$ where m is the mass flow rate of cooling water from the C.T.B., and ΔT is the temperature difference between the delivered and returned cooling water. Heat rate applied at the heated section has been calculated in the form $Q_{applied}=IV$ where I and V are current in amperes and voltage in volts, respectively. It has been assumed that two symmetrical heat exchangers share the heat load equally, thus each absorbing half the applied heat. As can be seen from the tab. 1, both measured (applied) heat rate and absorbed heat rate are very close to each other which means uncertainty in power measurements are actually very low. The precision of data collected helps construct a reliable Nusselt number correlation. These calculated heat rate values have been used to calculate the Nusselt numbers. Heat transfer calculations for heat exchangers have been performed solving the radial heat transfer problem in an assembly made up of two concentric pipes whose outer surface is insulated. However, due to the fact that the environmental temperature and the cooling water temperature are almost the same (20^{o}C), insulation actually has no importance. Fig. 3 shows the domain where the heat transfer calculations have been made. Heat transfer for the oscillating flow coefficient has been constructed in eq. (2):

$$\frac{Q}{\pi dL} = q = h_{in}\left(T_w - T_m\right)$$

(2)

Where T_w is the time averaged temperature inner wall temperature of the inner pipe of the heat exchanger and T_m is the time averaged temperature of the oscillating flow at the heat exchanger inlet. Prandtl numbers and other water properties have been calculated as functions of temperature for each experimental run according to the polynomials given by Dixon [15].

Table 1: Heat balance calculation for heat exchangers

Experiment	Stroke, m	N, rpm	$Q_{applied,}$ W	$Q_{absorbed,}$ W	Difference,%
1	0.130	5	300	148.8	0.8%
2	0.130	10	300	147.8	1.5%
3	0.130	15	300	151.3	-0.9%
4	0.130	5	400	196.5	1.7%
5	0.130	10	400	198.1	1.0%
6	0.130	15	400	197.5	1.3%
7	0.130	5	500	244.8	2.1%
8	0.130	10	500	250.9	-0.4%
9	0.130	15	500	248.0	0.8%
10	0.170	5	300	150.7	-0.5%
11	0.170	10	300	146.6	2.3%
12	0.170	15	300	149.8	0.1%
13	0.170	5	400	199.3	0.3%
14	0.170	10	400	201.1	-0.5%
15	0.170	15	400	202.0	-1.0%
16	0.170	5	500	248.1	0.7%
17	0.170	10	500	251.4	-0.6%
18	0.170	15	500	248.8	0.5%
19	0.195	5	300	148.6	1.0%
20	0.195	10	300	146.9	2.1%
21	0.195	15	300	151.4	-0.9%
22	0.195	5	400	201.7	-0.9%
23	0.195	10	400	201.6	-0.8%
24	0.195	15	400	195.8	2.1%
25	0.195	5	500	252.8	-1.1%
26	0.195	10	500	252.7	-1.1%

27	0.195	15	500	246.6	1.4%

Because the heat exchanger is a "parallel flow" one in half cycle whereas it is "counter flow" in the other half, it is necessary to calculate the logarithmic mean temperature differences (LMTD) separately for each half of the cycle. However, it turns out that the arithmetic differences and logarithmic mean temperatures are basically same and the difference is negligible due to the fact that inlet-outlet temperature differences of heated and cooled fluids are small.

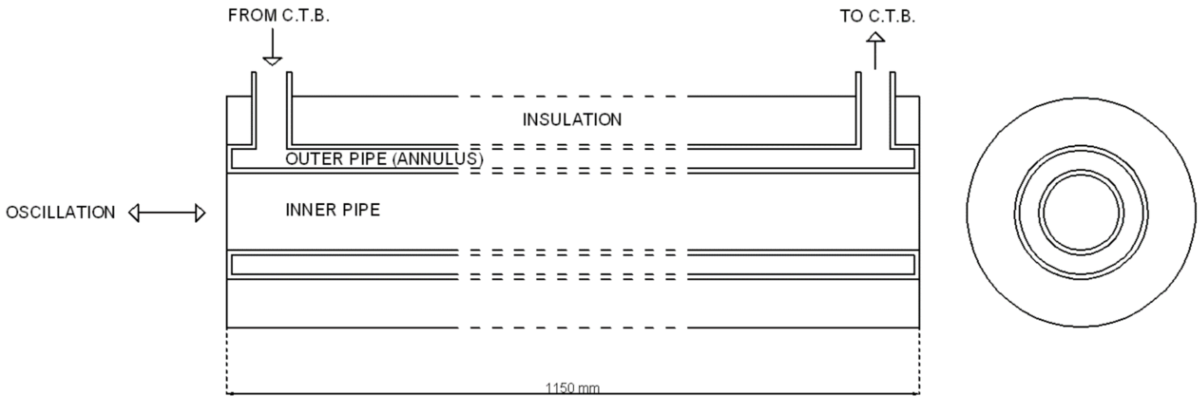

Figure 3 : Schematic of heat exchanger.

Nusselt number for unidirectional laminar annulus flow has been calculated using eq. (3) as given by Staton and Cavagnino [16]:

$$\mathrm{Nu}_{\mathrm{annulus}} = \frac{h_{\mathrm{annulus}} D_h}{k_w} = 7.54 + \frac{0.03\mathrm{RePr}\frac{D_h}{L}}{1 + 0.016\left[\mathrm{RePr}\frac{D_h}{L}\right]^{2/3}} \tag{3}$$

where D_h is the hydraulic diameter of annulus. Once the heat transferred is determined, radial heat transfer problem is solved for each experimental run to calculate the thermal resistance $\Sigma R=\Delta T/Q$ as given in eq. (4):

$$\Sigma R = \frac{1}{h_{in}\pi d L} + \frac{\ln\left(r_{out}/r\right)}{2\pi L k_s} + \frac{1}{h_{annulus}\pi d_{out} L} \tag{4}$$

Heat transfer coefficients h_{in} obtained eq. (4) have been used to calculate Nusselt number in eq. (5):

$$\mathrm{Nu} = \frac{h_{in} d}{k_w} \tag{5}$$

Nusselt numbers obtained in eq. (5) have been plotted against Re_ω for each non-dimensional A_o as shown in fig. 4 where A_o is the non-dimensional displacement length defined as $A_o=x_{max}/d$ and Re_ω is the kinetic Reynolds number defined as $Re_\omega=\rho\omega d^2/\mu$.

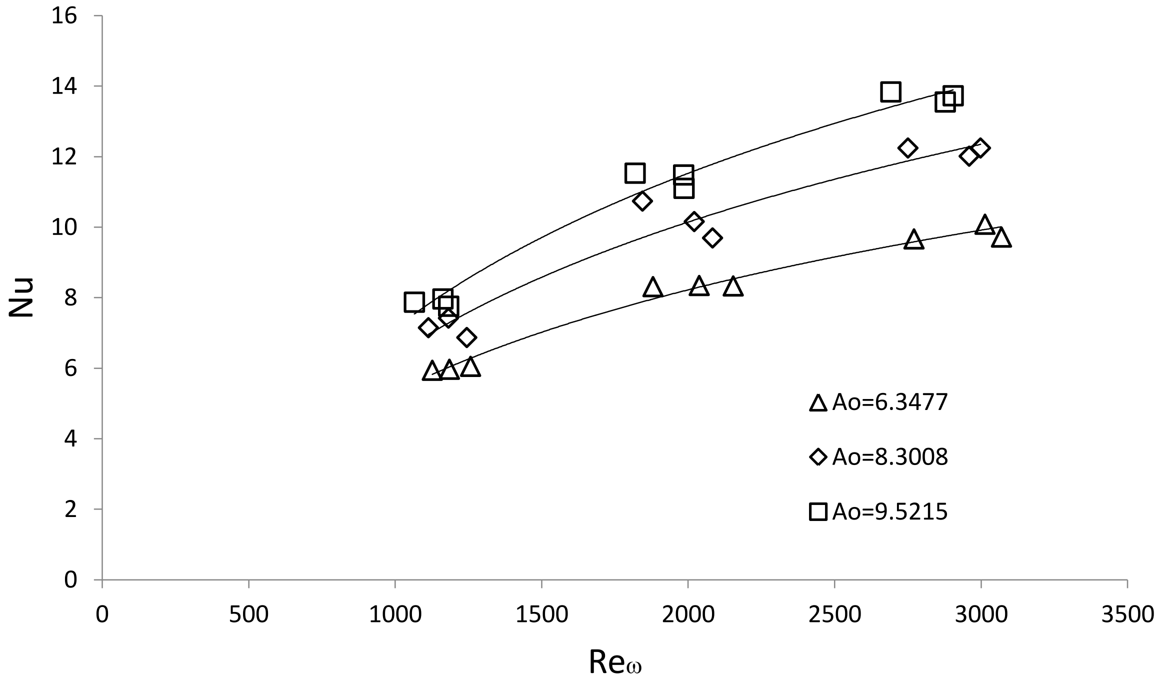

Figure 4 : Variation of Nusselt number with Kinetic Reynolds number.

Having obtained all the Nusselt numbers using 27 sets of experimental data. A non-linear correlation has been obtained utilizing IBM SPSS© nonlinear regression module in the form $Nu = aA_o^b Re_\omega^c Pr^d$ with the following parameters:

a=0.027
b=0.752
c=0.443
d=0.603

Thus the new correlation is given in eq. (6) as follows:

$$\mathrm{Nu} = 0.027\ \mathrm{A_o^{0.752}}\ \mathrm{Re_\omega^{0.443}}\ \mathrm{Pr^{0.603}} \tag{6}$$

This correlation is valid for $6.3477 < A_o < 9.5215$ and $1066 < Re_\omega < 3070$.

The works of previous researches such as Hausen's equation [17] Zhao and Cheng [9] to be compared with the new correlation are as follows:

Hausen's equation for cooled section:

$$\mathrm{Nu} = 3.3\mathrm{Wo}^{0.2} + \frac{0.041(\mathrm{A_d}/\mathrm{L_c})\mathrm{Wo}^2\mathrm{Pr}}{1 + 0.016\left[(\mathrm{A_d}/\mathrm{L_c})\mathrm{Wo}^2\mathrm{Pr}\right]^{2/3}} \tag{7}$$

Where A_d is the fluid displacement and L_c is the length of the cooled section.

Zhao and Cheng correlation:

$$\mathrm{Nu} = 0.02\mathrm{A}_{\mathrm{o}}^{0.85}\mathrm{Re}_{\omega}^{0.58} \tag{8}$$

Fig. 5 compares the experimental results with the new correlation above and with that of other researchers in the form Re_{ω} vs $Nu / A_o^{0.752}$

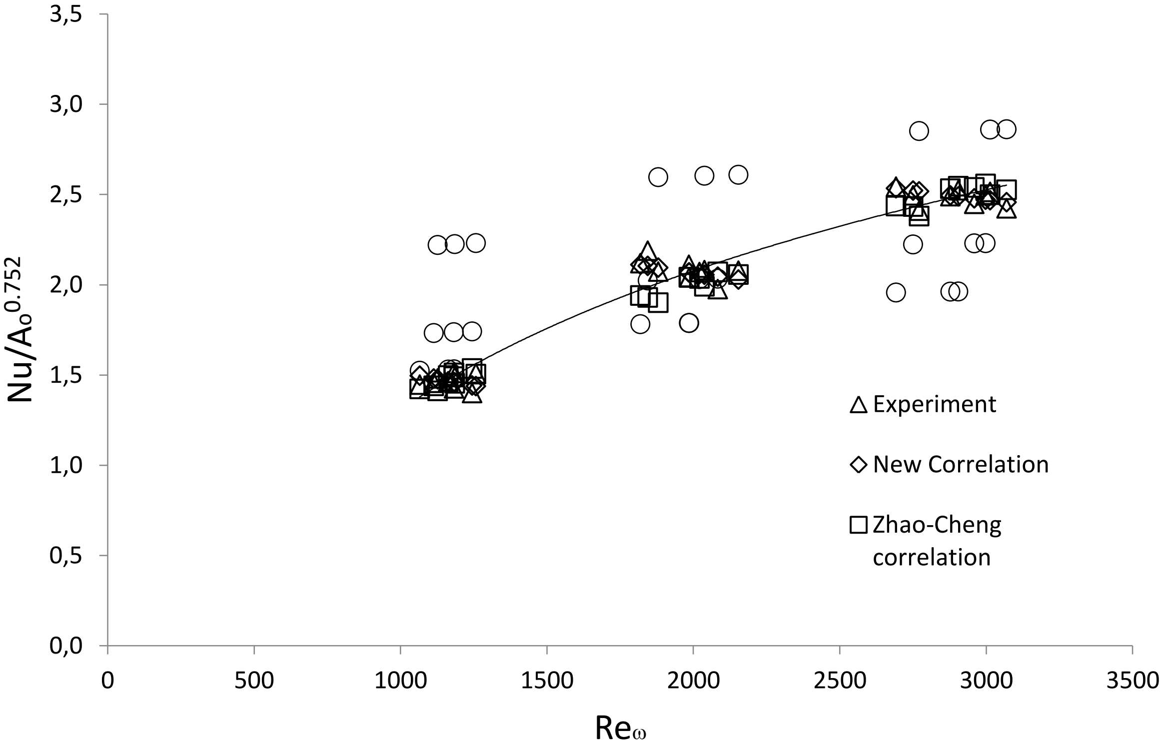

Figure 5 : Comparison of experimental $Nu / A_o^{0.752}$ with various correlations.

Conclusion

In this experimental study, heat transfer in oscillating flow where water is the flow medium has been studied. A wide range of experiments where a double acting piston-cylinder system is used for reversing the flow, has been conducted. Oscillating flow amplitude and frequency variations have been obtained using different piston stroke settings and A/C motor drive frequency settings, together with three different settings of heat input. The acquired raw temperature data have been reduced to obtain a new correlation of Nusselt number through a series of heat transfer calculations. Amplitude and frequency has limited effect on enhancement of heat transfer, as can be seen from the correlation. Nusselt number correlation obtained herein has been compared to those found in the literature and it is considered to be a good representation of the oscillating flow heat transfer aspects, thus a reliable tool to estimate the heat transfer, owing to the fact that it takes into account the effect of Prandtl number which considerably changes with temperature variations.

Acknowledgements

I would like to express my thanks to Istanbul Technical University whose financial support and granting access to its laboratory facilities made it possible to realize this experiment.

Nomenclature

d	inner diameter diameter of concentric heat exchanger's inner pipe, [m]
D	inner diameter diameter of concentric heat exchanger's outer pipe, [m]
A	cross-sectional area of concentric heat exchanger's inner pipe, [m]
A_p	cross-sectional area of double acting cylinder, [m^2]
k	conduction coefficient, [$Wm^{-1}K^{-1}$]
I	current, [A]
L	length of the concentric heat exchanger, [m]
n	frequency output of A/C drive, [1/s, Hz]
N	rotational speed of reducer motor, [rpm]
h	heat transfer coefficient, [$Wm^{-2}K^{-1}$]
Nu_L	space-cycle averaged Nusselt number ($=hd/k_w$), [-]
Q	Joule heating obtained from ribbon heaters, (=IV), [W]
q	heat flux at the wall, [Wm^{-2}]
R	radius of flywheel, [m]
Re_d	pipe diameter based Reynolds Number ($=\rho u_m d/\mu$), [-]
Re_ω	kinetic Reynolds Number ($=\rho\omega d^2/\mu$), [-]
Wo	Womersley Number ($=0.5Re_{\omega}^{0.5}$), [-]
t	time, [s]
u_m	cross-sectional mean fluid velocity, [ms^{-1}]
u_{max}	amplitude of mean fluid velocity, [ms^{-1}]
x_p	maximum displacement of the piston (stroke) , [m]
x_m	temporal fluid displacement at the inlet of the heat exchanger, [m]
x_{max}	maximum fluid displacement in concentric heat exchanger's inner pipe, [m]
A_o	non-dimensional displacement ($= x_{max}/d = 2Re_d/Re_\omega$), [-]
C_p	constant pressure specific heat, [$Jkg^{-1}K^{-1}$]
Pr	Prandtl number, [-]
T	temperature, [^oC]
V	voltage, [V]

Greek Symbols:

ρ	density, [kgm^{-3}]
ω	angular frequency, [$rads^{-1}$]
ν	kinematic viscosity, [m^2s^{-1}]
μ	dynamic viscosity, [Pa.s]

Subscripts:

max	maximum
p	piston
s	solid

w water

References

[1] Akdag U., Ozguc, A.F., Ozdemir, M., The experimental and theoretical investigation of heat transfer in oscillating flow by control volume approach, *Journal of Thermal Sciences and Technology*, 28 (2008), 1, pp. 23-31

[2] Ozdemir, M., Ozguç, A.F., A simple mathematical model to analyse a Fluidyne heat machine, *Proceedings of the Institution of Mechanical Engineers, Journal of Power and Energy,* 217(2003), 1, pp. 91-100

[3] Akdag, U., Ozdemir M., Heat transfer in an oscillating vertical annular liquid column open to atmosphere, *Heat Mass Transfer,* 42(2006), pp. 617–624

[4] Arslan G., Ozdemir M., Correlation to predict heat transfer of an oscillating loop heat pipe consisting of three interconnected columns, *Energy Conversion and Management* ,49(2008), 8, pp. 2337-2344

[5] Akdag. U., Ozdemir and M., Ozguc. A.E., Heat removal from oscillating flow in a vertical annular channel, *Heat Mass Transfer,* 44 (2008), pp. 393–400

[6] Zhao. T.S., Cheng. P. , Heat Transfer In Oscillatory Flows, *Annual Review of Heat Transfer*, Volume IX, 1998

[7] Shahin. G. A., The Effect of Pulsating Flow on Forced Convective Heat Transfer, Ph. D. thesis, The University of Western Ontario, London, Ontario, Canada, 1998

[8] Walther, C., Kühl, H. and Schulz, S., Numerical investigations on the heat transfer in turbulent oscillating pipe flow, *Heat and Mass Transfer,* 36(2000), pp. 135-141

[9] Zhao, T., Cheng, P., Oscillatory Heat Transfer In A Pipe Subjected To A Laminar Reciprocating Flow, *ASME Journal of Heat Transfer*, 118 (1996), pp. 592-598

[10] Bouvier. P., Stouffs. P. and Bardon. J., Experimental study of heat transfer in oscillating flow, *International Journal of Heat and Mass Transfer*, 48 (2005), pp. 2473–2482

[11] Akdag, U., Ozguc, A.F., Experimental investigation of heat transfer in oscillating annular flow, *International Journal of Heat and Mass Transfer*, 52(2009), 11, pp. 2667-2672

[12] Gul, H., Experimental investigation of heat transfer in oscillating circular pipes: High frequencies and amplitudes, *Academic Journals,* 8(2013), 13, pp. 524-531

[13] Zhibin, Y., Xiaoan, M. and Jaworski, A., Experimental study of heat transfer in oscillatory gas flow inside a parallel-plate channel with imposed axial temperature gradient, *International Journal of Heat and Mass Transfer*, 77(2014), pp.1023-1032

[14] Figliola, R.S., Beasley, D.E., Theory and Design for Mechanical Measurements, John Wiley and Sons Inc., New York, USA, 2006

[15] Dixon, J., Shock Absorber Handbook, John Wiley and Sons Inc., New York, USA, 2007

[16] Staton, D. A., Cavagnino, A., Convection Heat Transfer and Flow Calculations Suitable for Electric Machines Thermal Models, IEEE Transactions of Industrial Electronics, 55(2008), 10, pp. 3509 - 3516

[17] Fan, A.. Fulmer, D. and Hartenstine. J., Experimental Study of Oscillating Flow Heat Transfer, Proceedings, First International Conference on Micro/Nanoscale Heat Transfer, Tainan, Taiwan, 2008, pp. 347-354