Proceedings of the World Congress on Engineering 2010 Vol II
WCE 2010, June 30 - July 2, 2010, London, U.K.

Air Pressure Dependence of Natural-Convection Heat Transfer

Maysam Saidi, Reza Hosseini Abardeh

Abstract— **Heat transfer is one of the prevalent concepts with many usages in different fields of science, industry and so on. In different applications we need more or less to know about this phenomenon. Control of this phenomenon is too important in some cases and we should be aware how to control it. The importance of heat transfer rate and effect of various parameters on it, is a reason of performing this research. Because of changes of air pressure in different applications, we need to know how heat transfer affected by air pressure. In different places air pressure is higher or lower than atmospheric pressure and we can't use more of experimental equations (e.g. Morgan or Churchill-Chu for a horizontal cylinder) which correlated in standard situation and atmospheric pressure so air pressure changes haven't been calculated. In this paper an experimental study was done in order to investigate the effects of air pressure on natural convection heat transfer from a horizontal cylinder specimen. In this experimental study tests have been done in continuum mechanics range. By using a particular apparatus with ability to change specimen surround Pressure, natural convection calculated by existent equations. Pressure varied from 18 to 220000 Pascal and convection coefficient was calculated in the temperature range from 40 to 100 C. Each test has been done in repeatedly to have high precision. Various diagrams and tables were obtained to show pressure dependence of natural convection. Reduction of convection coefficient was observed by reduction of air pressure and order of these changes is shown in different figures. Vice versa natural convection, radiation is not depend on air pressure so percentages of two types of heat transfer (convection and radiation) are different due to various pressures, and this concept is observed in this literature. Although tests have been done in several input powers but in each pressure, natural convection only had dependency on temperature, and different input powers led to same results. Main aim of this work is to show the rhythm of convection changes in a range of pressure. Also in different temperatures this rhythm can be seen.**

Index Terms— ***Air pressure, Horizontal cylinder, Natural convection***

I. Introduction

Natural convection has a lot of benefits as a mechanism of heat transfer. In many parts, convective heat transfer plays an important role in heat transfering. In some cases rate of heat transfer is important and it's vital to predict it. Various parameters effects on the rate of heat transfer and considering this, can improve our calculations. It is obvious that convection is caused by density variation of fluid molecules. Surrounded air of a specimen has a molecular density that relates to its pressure. So, it's clear that various pressure causes various convective heat transfer. Style of this relation is important to be observed.

Natural convection from a horizontal cylinder is one of common problems that have widespread usages in different fields. Many studies have been done to investigate heat transfer from a horizontal cylinder in air standard pressure. Morgan [1] and Churchill-Chu [2] have derived the most important correlations in this problem. Although theses correlations and the others are used widely but we should consider they are suitable only in standard air pressure and deviation from atmospheric pressure causes error.

Air pressure varies in different places due to altitude and other things like latitude, weather condition and temperature difference. It is possible that air pressure decreases or increases in a container which heat transfer rate from an internal part of it, is important. This situation leads us to think about the importance of pressure changes on natural convection heat transfer. Despite many works have been done to observe natural convection heat transfer, but little of them are in non-atmospheric pressure. One of works has been done by Deviene [3] that he categorized air density to four categories by its Knudsen number. He concentrated on rarefied air and attained correlation for natural convection between two plates. Kyte et al. [4] studied natural convection from spheres and cylinders in reduced air pressures. Besides air, they have done same tests for other gas (Helium and Argon) and have shown different results for different gases. Hirano et al. [5] did experimental study to observe natural convection from a cube in low pressures. Hosseini and Taherian [6] also did same studies for a vertical plate.

Totally, works in this field are inadequate and new works seems inevitable. Extensive range of pressure -higher and lower than atmospheric pressure- has been examined in this study. Observing natural convection coefficient changes and changing dominance between radiation and convection are important aims of this work. Although this work has been done for one specimen, but it is clear that changing rhythm is same in different sizes of elements.

II. Experimental Setup and Procedure

Tests have been done by a horizontal cylinder specimen that was placed in a steel cylinder vessel. The specimen has 6.35 mm diameter and 160 mm long. Its material is copper and finished with matt black surface. It was heated by an internal heater and electrical power was conducted by two wires on its both sides. Its surface temperature was measured by a thermocouple at the mid-point. The specimen was sufficiently remote from the walls of the vessel to give substantially free convection.

Manuscript received March 15, 2010.
Maysam Saidi is M.Sc. student of Mechanical Engineering at Sharif University of Technology, Tehran 11365-8639, Iran (corresponding author, phone: +989188318006; e-mail: msaidi@mech.sharif.edu).
Reza Hosseini Abardeh is associate professor of Mechanical Engineering at Amirkabir University of Technology, Tehran 15875-4413, Iran (e-mail: hoseinir@aut.ac.ir).

The vessel pressure can be changed by a vacuum pump and a compressor which was attached to vessel. We use compressor for increasing and vacuum pump for decreasing air pressure than atmospheric pressure. The vessel pressure is measured by transducers on its surface.

All needful data are monitored in control cabinet. It shows input power, vessel pressure and temperature of vessel and specimen. We can also adjust input power and vessel pressure to desired value. Fig. 1 shows apparatus parts.

Tests of this study have been done in 9 different pressures. Atmospheric pressure of laboratory was 88500 Pascal and 4 other pressure below and 4 other pressure above this pressure also tested. Test was repeated with different input powers to attain more accuracy for each pressure. The cylindrical specimen was heated in a specific pressure and input power. After being steady, the initial temperature of the specimen was recorded and after turning the heater off the specimen started becoming cold. This temperature was recorded every ten seconds.

The vessel wall temperature was 300 K and it was the same in different times. Test pressure was varied from 18 to 220000 Pascal. Cooling rate was variable in different pressure and different specimen temperature. For each pressure 5 or 7 different input power was used and results were same for each input power.

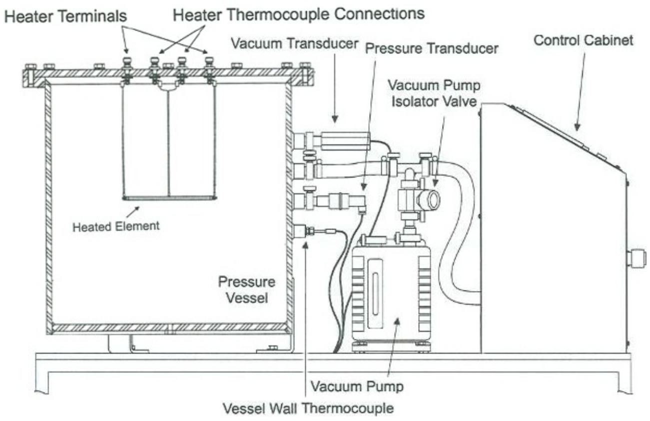

Fig. 1 Schematic presentation of the experimental apparatus

III. Results and Discussion

We assume a control volume for the horizontal cylinder specimen and data analysis has been done by using 1st law of thermodynamic or conservation of energy principle. Output energy includes radiation and convection that is equal to changes of specimen internal energy. After simplifying this relation, convection coefficient is shown in (1).

$$h_{conv} = \frac{mc_P\left|\frac{dT_E}{dt}\right| - \varepsilon\sigma A(T_E^4 - T_\infty^4)}{A(T_E - T_\infty)} \qquad (1)$$

Emissivity of specimen is 0.96 in test temperature range. Also we know that specimen material properties and deal of its surface and volume. Table (1) shows needful data.

Table 1 Specimen needful data

Property	**Units**	**Amount**
ρ	kg/m^3	8933
C_p	J/kg.K	385
A	m^2	3.68E-03
V	m^3	5.07E-06

As described in last session after reaching steady condition and turning off input power the specimen starts cooling and specimen temperature decreases by losing heat through radiation and convection till reaching surround temperature. We able to draw cooling curve by recording these data. Table (2) shows maximum or steady specimen temperature which accessible in each pressure and input power. Different input powers are symbolized by C to I to make easy for future referral.

Table (2) shows reverse relation between air pressure and specimen steady temperature. More air pressure causes better heat transfer because of convection more importance. Higher pressure causes less heat transfer resistance and maximum temperature -steady temperature- decreases in a specific power.

Table 2 Specimen steady temperature at different powers and pressures

I.Power / Pressure	**7.10 W**	**6.88 W**	**5.92 W**	**4.76 W**	**3.74 W**	**2.79 W**	**1.81 W**
symbol	C	D	E	F	G	H	I
18 Pa	196 °C	181 °C	166 °C	152 °C	133 °C	111 °C	85 °C
1000 Pa	183 °C	170 °C	156 °C	142 °C	124 °C	103 °C	80 °C
10000 Pa	164 °C	152 °C	139 °C	126 °C	108 °C	90 °C	70 °C
43000 Pa	149 °C	138 °C	126 °C	113 °C	97 °C	82 °C	65 °C
88500 Pa	137 °C	126 °C	115 °C	103 °C	88 °C	75 °C	59 °C
110000 Pa	133 °C	122 °C	110 °C	100 °C	86 °C	-	-
150000 Pa	128 °C	118 °C	106 °C	95 °C	83 °C	-	-
185000 Pa	124 °C	114 °C	103 °C	93 °C	81 °C	-	-
220000 Pa	120 °C	109 °C	100 °C	90 °C	78 °C	-	-

Fig. 2 shows cooling curves of specimen that recorded every ten seconds and represents specimen temperature in different times and selected pressures. Rate of cooling is higher in initial times than the final. As seen in (1) we need dT/dt so we should derivate from these curves. We fitted proper curve on discrete data, then calculated and drew dT/dt curves. Now, we can explain dT/dt of specimen in every temperature of test. We prospect that rate of temperature differences in specific temperature should be same in different input powers and it is obvious in Fig. 3.

ISBN: 978-988-18210-7-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

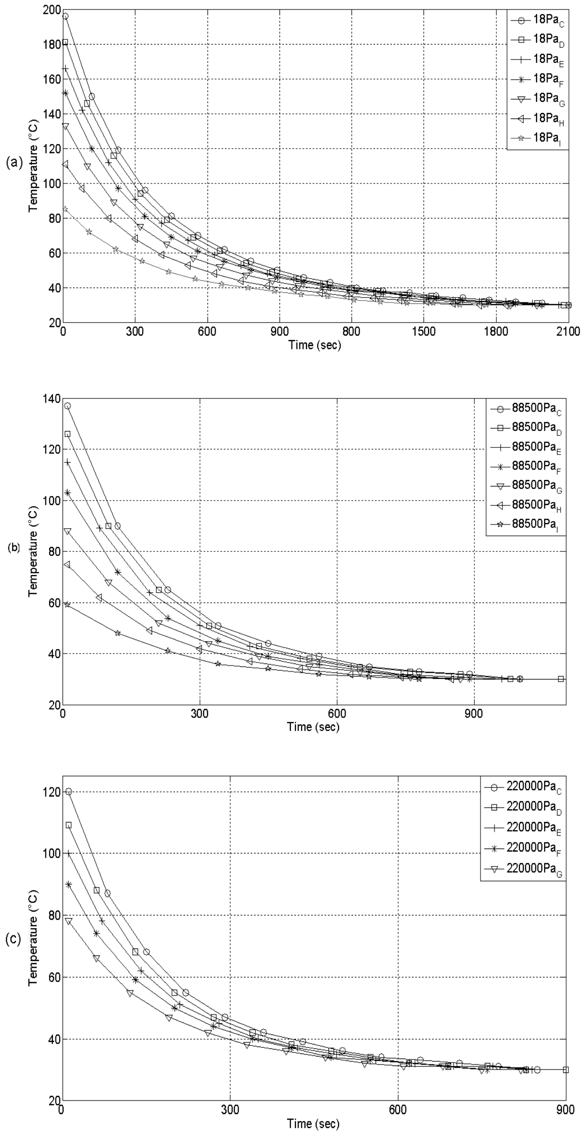

Fig. 2 Cooling curves, variation of the specimen's temperature with time for different initial input power and three selected pressure: a)18Pa, b)88500Pa, c)220000Pa.

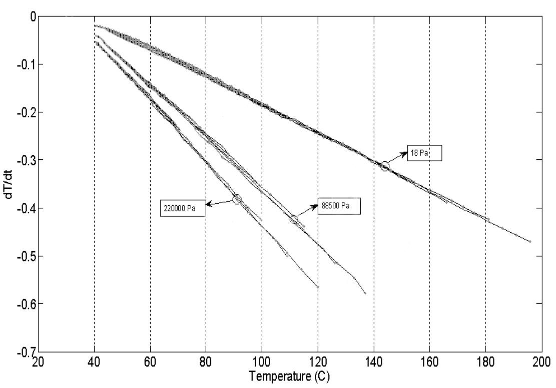

Fig. 3 Temperature derivative with time vs. temperature at different pressures and input powers

Rate of temperature differences is increased by temperature and pressure. Molecular movement increases and this in turn leads to more convective heat transfer. Convection coefficient can be calculated by (1) and is shown in Fig. 4. Effect of different pressures on convection coefficient is displayed in this figure. Multiple data recordings in different input powers make certain for results. As we prospect, pressure increase causes convection coefficient increase and this figure shows this dependency circumstance. Also, convection coefficient depends on temperature of specimen boundary layer which relates to specimen temperature and we see this dependency too.

Radiation coefficient depends on specimen surface, emissivity, specimen and surround temperatures and they have no pressure dependency. Two types of heat transfer, radiation and convection, have different proportion in different pressures. In low density air convection can be neglected and radiation has majority but in high air pressure this ratio will be switched. Fig. 5 shows radiation coefficient in different temperature for test condition and is same in different pressures. Table (3) uses these two figures to contrast each method role in different pressures.

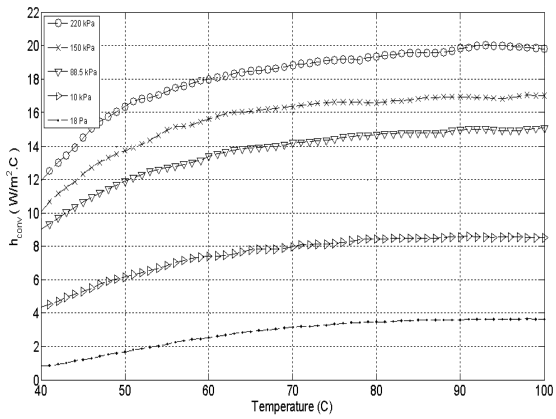

Fig. 4 Convection heat transfer coefficient with temperature at different pressures

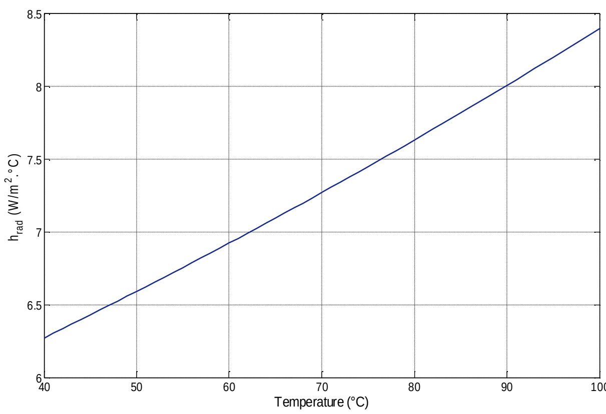

Fig. 5 Radiation coefficient with time

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Table 3 Variation of radiation and convection coefficient at different pressures and temperatures

Temp (C) ↓	Pressure (Pa) →	18	1000	10000	43000	88500	110000	150000	185000	220000
40	h_{Conv}	0.86	1.78	4.35	7.02	9.01	9.73	10.06	11.17	11.93
	h_r	6.27	6.27	6.27	6.27	6.27	6.27	6.27	6.27	6.27
50	h_{conv}	1.70	3.12	6.16	9.27	11.90	12.84	13.72	14.87	16.36
	h_r	6.59	6.59	6.59	6.59	6.59	6.59	6.59	6.59	6.59
60	h_{conv}	2.56	4.14	7.40	10.54	13.36	14.47	15.61	16.72	17.98
	h_r	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92
70	h_{conv}	3.16	4.74	7.99	11.44	14.17	15.62	16.37	17.80	18.85
	h_r	7.27	7.27	7.27	7.27	7.27	7.27	7.27	7.27	7.27
80	h_{conv}	3.47	5.11	8.44	11.70	14.67	15.83	16.59	18.32	19.35
	h_r	7.63	7.63	7.63	7.63	7.63	7.63	7.63	7.63	7.63
90	h_{conv}	3.60	5.30	8.56	12.01	14.95	16.14	16.92	18.47	19.64
	h_r	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
100	h_{conv}	3.51	5.24	8.52	11.99	15.06	16.16	17.02	18.48	19.80
	h_r	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39

Convection coefficient is nearly 8 times less than radiation coefficient in 18 Pascal and 40 Celsius. But this relation becomes about two times more than radiation in 220 kPa and same temperature. This manner repeated in other temperatures.

For verification of the results with other researches or available correlations in literature, the obtained heat transfer coefficients are compared with correlations for atmospheric pressure suggested by Morgan(1975), Churchill and Chu (1975). Comparison of results is shown in table 4 with the percentage of the differences. The present experimental results at atmospheric pressures are closer to the correlation suggested by Morgan. Unfortunately for other pressures the results could not be compared because no empirical or experimental results were available. However, the maximum expected errors are less than 20%.

Table 4 Comparison of the results for convection heat transfer coefficient of the present work with others at Atmospheric pressure.

Cylinder Temperature T_s(C)	Morgan correlation[1] h_{conv} (W/m^2.K)	Churchill and Chu[2] h_{conv} (W/m^2.K)	Present Work h_{conv} (W/m^2.K)	% of differences with Morgan	% Of differences with Churchill and Chu
40	10.30	8.48	9.01	-12.5	+6.25
60	12.25	10.16	13.36	+9.06	+31.50
80	13.39	11.17	14.67	+9.56	+31.33
100	14.22	11.90	15.06	+5.91	+26.55
120	14.89	12.49	15.00	+0.74	+20.10

IV. CONCLUSION

Natural convection heat transfer from a horizontal cylinder is affected by air pressure. Higher air pressure causes better heat transfer and reduces heat transfer resistance. The steady temperatures of test specimen show this statement where for example at same input power the steady temperature decreases from 196 to 120 by changing of pressure from 18 to 220,000 Pa. As these tests have been done in different input powers but in each pressure results had dependency to temperature and different input powers had same results.

In tests pressure range the convection coefficient can become ten times more only by changing air pressure. Also the pressure changes cause changes in ratio of heat transfer role between radiation and convection. In rarefied air, radiation has the priority but at high pressure this priority lessened and convection becomes more important. For example at 60 Celsius temperature, although the radiation coefficient is same on different pressures but the convection coefficient becomes 7 times more on 220 kPa than 18 Pa. this rhythm repeats on different temperatures.

By pressure increasing, the convection coefficient doesn't increase linearly and seems to reach constant value. As a result of air molecules motion, although more heat is transferred but more motion in turn makes more contact and this is the cause of this behavior.

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