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Cooling of Superheated Refrigerants Flowing Inside Mini and Micro Tubes, Study of Heat Transfer and Pressure Drop, CO_2 Case Study

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Abstract

Superheated Carbon dioxide gas was subjected to a cooling process. Experimental investigation along with an analytical study was carried out in this work. This work is intended to be part of the super critical Gustav Lorentzen refrigeration cycle of CO2. Experimental and analytical works concentrated on heat transfer and pressure drop for single phase flow during gas cooling inside mini and micro tubes. Empirical correlations were formulated analytically for the coefficient of convectional heat transfer and for the pressure drop in the following forms:

$Nu = 0.24\ (Re)^{0.53}\ (Pr)^{0.43}$

And

$Eu = 1.1*10^{-4}\ (ReD)^{-0.26}\ (L/D)^{1.06}$

Correlations were validated against some experimental results and compared to all experimental results and other literature correlations; an agreement of more than 90% was noticed. This work can enhance the calculations of heat flux and pressure drop of gases flow inside mini and micro tubes. It can also help in the design procedure of heat exchangers and cooling processes.

Keywords: Cooling refrigerants; Inside flow; Mini and micro tubes; Heat transfer; Pressure drop; R477

Nomenclature

Eu	Euler Number, ($\Delta P/ \rho V2$)
ReD	Reynolds Number,($\rho VD/\mu$)
L/D	length/diameter for tubes.
Pr	Prandtl number, (Cp μ/K)
Ra D	Ralighs number, (β g ΔT D3/$\upsilon\alpha$)
T	Temperature, K or oC.
P	Pressure, kPa.
m	Mass flow rate, kg/s
h	Heat transfer coefficient, kJ/m2.k

Latin

Δ	Delta
ρ	Density, kg/m3
μ	Dynamic viscosity, m.s

Superscript

m,n Exponents constants

Subscript

LMTD	Log. mean temperature difference
i	Inner
o	Outer

1. Introduction

Heat transfer and fluid flow inside tubes have many applications. Heat exchangers, condensers, evaporators and boilers are examples of these applications. Literature shows many recent studies of heat transfer for single phase flow inside tube two of them are: Gopenath, [1] and Kim, [2].

Equations and correlations were formulated and validated by experimental work. Different correlations are now in use to calculate heat transfer coefficients and pressure drop. These correlations can be found in text books and papers of heat transfer, for example, Bejan [3], Incropera [4], and Liao [5].

The experimental and analytical work in this study covered a domain of independent parameters as follows; the inner tube diameter ranged from 0.6 mm up to 1.6 mm, the saturation temperature ranged from -15 ^{o}C up to 15 ^{o}C, the mass rate of flow ranged from 2.5 $*10^{-5}$ kg/s up to 17 $*$ 10 $^{-5}$ kg/s and the pressure ranged from 30 bars up to 50 bars.

Table 1 shows correlations for heat transfer Nu and pressure drop friction factor, *f*, during flow inside tubes. These are just examples of the published literature works, with all variables involved presented. These

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studies showed an acceptable agreement between experimental values of heat transfer coefficient and those calculated using the correlations predicted.

Table 1: Literature correlation formulae for single phase flow inside tubes.

No	Reference	Correlation	Case
1.	Incropera and Dewitt [2]	$Nu_D = 0.023 (Re_D)^{4/5} (Pr)^{1/3}$	Colburn equation.
		$f = (0.790 \ln Re_D - 1.64)^{-2}$ and $\Delta P/\Delta X = f\,(\rho V^2/2)/D$	Petukhov equation for pressure drop.
2.	Bejan [3]	$Nu_D = 0.027 (Re_D)^{4/5} (Pr)^{0.3}$	Cooling, Dittus-Boelter equation.
		$f = 0.079\, Re_D^{-0.25}$ and $\Delta P/\Delta X = f\,(\rho V^2/2)/D$	$2*10^3 < Re_D < 2*10^4$

2. Experimental

Figure 1 shows a schematic diagram of the used test apparatus. Cooling and condensation occurred inside a chest freezer with lowest possible air temperature of -28°C. The Data Acquisition System (DAS) of model SCX14, made by National Instruments was used with LAB VIEW software for processing. Visual and printed reports were the output of the experiments. Fifteen temperature readings were sensed by K – type thermocouples and fed to the DAS simultaneously.

The pressure was read in two points at steady state conditions and they were before cooling and at condensation. Volumetric rate of flow in m^3/s was read at the end outlet flow by a gas flow meter calibrated for CO_2 at room temperature and local pressure conditions.

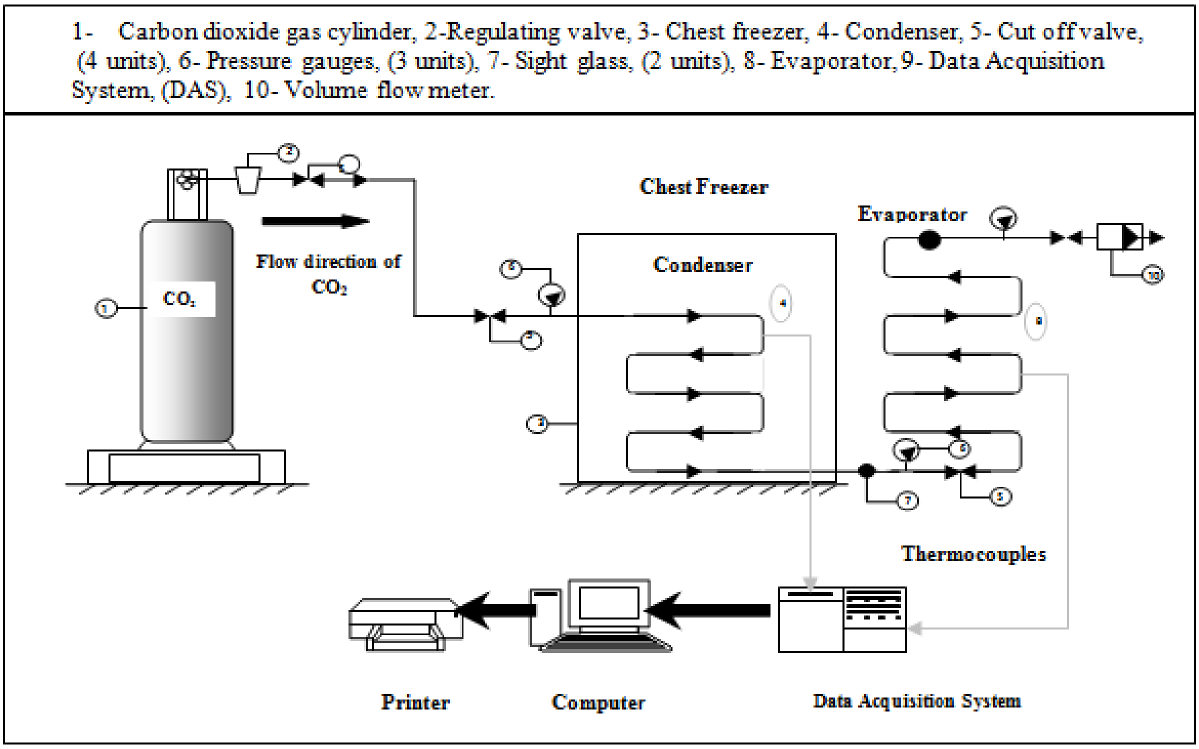

Figure1: Schematic diagram of the experimental unit.

2.1. Heat Transfer:

The tube outside surface temperatures at 15 points along the whole test sections (about 15 m), were measured by thermocouples fixed on the outer surface of the tube and covered with an insulation spot glue at longitudinal locations. These temperatures were tabulated along with the test section length. Two pressure values and volumetric rate of flow were tabulated also. Different experiments were carried out by changing independent variables; the pipe diameter, D, (three different values), test section inlet pressure, Pin, (four different values), and rate of flow, V, (four different values).

The total length of the cooling and condensation portion was about 15 meters. This study is concerned only with the first line which shows the process of cooling only.

Figure 2 shows the pipe longitudinal distribution of the tube outer surface temperatures of a typical cooling experiment. The figure shows a gas cooling part and a condensation part. The two lines are with different slopes.

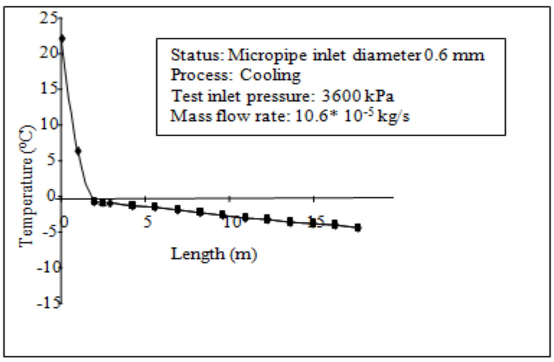

Figure 2: Tube outside wall surface temperatures measured points in °C versus test section length during cooling and condensation process inside the chest freezer of – 28 °C.

Heat released by the gas while cooling formed a radial heat flux. Convection and conduction heat transfer occurred. Heat balance for the heat transfer inside the chest freezer was modeled by the following equations:

$$Q_{CO2} = h_o A_o \Delta T_{lmo} \quad (1)$$

$$Q_{CO2} = C_p (T_1^{/} - T_2^{/}) \quad (2)$$

$$Q_{CO2} = h_i A_i \Delta T_{lmi} \quad (3)$$

Where the outer logarithmic mean temperature difference equals:

$$\Delta T_{lmo} = [(T_1 - T_a) - (T_2 - T_a)] / \ln [(T_1 - T_a) / (T_2 - T_a)] \quad (4)$$

And the inner logarithmic mean temperature difference equals:

$$\Delta T_{lmi} = [(T_1^{/} - T_1) - (T_2^{/} - T_2)] / \ln [(T_1^{/} - T_1) / (T_2^{/} - T_2)] \quad (5)$$

Where T_1 and T_2 are the first and last temperatures of the wall outside surface, $T_1^{/}$ and $T_2^{/}$ are the gas inlet and outlet mean temperatures and T_a is the deep freezer air temperature around the tube.
Where, also A_o and A_i are the outer surface tube area and the inner surface tube area respectively.

The h_o and the h_i are the outer and inner heat transfer coefficient respectively.

Equation 1 will be used to calculate the heat quantity using Churchill and Chue formula to calculate h_o, the formula is [4]:

$$Nu_D = \{0.60 + ((0.387\, R_{aD}^{1/6}) / [1 + (0.559/P_r)^{9/16}]^{8/27})\}^2 \quad (6)$$

Equation 2 will be used to calculate the mean gas flow temperature at inlet, ($T_1^{/}$) as the gas temperature at exit is known to equal saturation temperature at measured pressure.

Then equation 3 will be used to calculate the mean heat transfer coefficient of CO_2 at the inner surface flow of the tube. In this step conduction heat transfer through the tube wall was neglected.

This will be the experimental heat transfer coefficient, (h_{exp}.) for cooling gaseous CO_2. This was calculated and abulated.

2.2. Pressure Drop:

To determine the pressure drop, it was convenient to work with the Moody (or Darcy) friction factor, which is a dimensionless parameter defined as [4]:

$$f = \frac{-(dP/dx)D_i}{\rho u_m^2 / 2} \quad (8)$$

Where, *f* is the friction factor, which can be either extracted from Moodies chart, or calculated using Petukhov equation as [4]:

$$f = (0.790 \ln Re_D - 1.64)^{-2}, \quad 3000 < Re_D < 5*10^6$$

(For turbulent flow) (9)

The length of the cooling region (L) was 1.9 meters as mentioned before.

Pressure drop, ΔP was calculated using equation 8 mentioned before and the value of *f* was extracted from Moodies chart. This data was tabulated and will be used later as experimental pressure drop values, $\Delta P_{exp.}$

2.3. Uncertainty Analysis for Experimental Work:

The uncertainty in the experimental calculated result is computed using the known Kline and McClintock following relation:

$$W_r = [(\frac{\partial R}{\partial X_1} W_{X1})^2 + (\frac{\partial R}{\partial X_2} W_{X2})^2 + ... + (\frac{\partial R}{\partial X_j} W_{Xj})^2]^{1/2} \quad (10)$$

Where: W_r is the uncertainty in the results; W_j is the uncertainty in each basic measurement, and the Partial derivatives $\frac{\partial R}{\partial X_j}$ are the sensitivities.

Calculations gave the following value:

$W\, h_{exp} = \pm\ 1.28$ W/ m^2.K

This is less than 1%, of the original value.

And

$W\, \Delta P_{exp} = \pm\ 1.0$ kPa.

This is around 6.5% of the original value.

3. Analytical Work

3.1. Convection Heat Transfer:

The Reynolds numbers of the experimental carried out in this work ranged from 3000 up to 15,000. Turbulent flow could be assumed and Colburn equation was used as a basic equation to calculate the convectional heat transfer coefficient. Colburn equation is in the form of Incropera, [4]:

$$Nu_D = C\, Re_D^m\ Pr^n \quad (11)$$

Where C is a constant, m and n are exponent constants.

Over the range of the Re_D and Pr values considered within this work domain, the values of the constants: C; m; and n were evaluated: 0.24; 0.53; and 0.43 respectively. The correlation for heat transfer relation between Nu_D, Re_D and Pr for CO_2 cooling super heated gas was formulated in the form:

$$Nu_D = 0.24\, Re_D^{0.53}\, Pr^{0.43} \quad (12)$$

3.2. Pressure Drop:

All references in the literature deal with pressure drop (ΔP) inside tube gas flow as a function of many variables shown in the following equation:

$$\Delta P = f(Re_D, V, L, D, \rho) \quad (13)$$

Analytical work manipulating equation 11 with non-dimensional terms revealed the following correlation in the form:

$$Eu = f\,(Re_D, L/D) \quad (14)$$

And this may be written as:

$$Eu = C\,Re_D^{\,m}\,(L/D)^{\,n} \quad (15)$$

The values of the constants: C; m; and n were evaluated: $1.1*10^{-4}$; -0.26 and 1.06 respectively. The pressure drop correlation for CO_2 can be put in the form:

$$Eu = 1.1 * 10^{-4}\,(Re_D)^{-0.26}\,(L/D)^{1.06} \quad (16)$$

4. Results Discussion

Figure 3 shows comparison between the experimental and correlation results of heat transfer coefficient, h_i. Two correlations were considered and each was compared with the experimental results: Colburn equation and this study correlation.

It is clear from the figure that h values of this work agrees with both the experimental results and those calculated using Colburn equation [4]. The agreement reached more than 0.98 with the experimental results and about 0.95 with Colburn results.

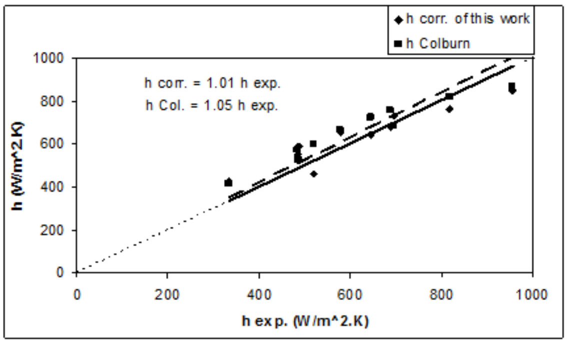

Figure 3: Experimental heat transfer coefficient Vs two correlation calculated values a) Using Colburn equation, b) Using this study correlation.

Figure 4 shows comparison between the experimental and correlation results of Nusselt number, Nu. Both Colburn equation and this study correlation were compared with the experimental results.

It is clear from the Figure that Nu values of this work agree with both the experimental results and those calculated using Colburn equation. The agreement of each one of the correlation with the experimental results reached about 0.92 for this study results and about 0.91 for Colburn results.

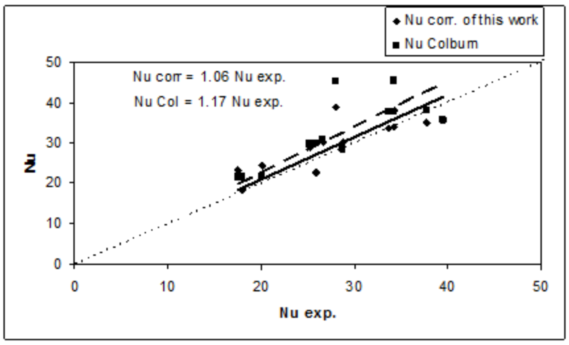

Figure 4: Experimental Nusselt number, Nu Vs two correlations calculated values a) Using Colburn equation, b) Using this study correlation.

Figure 5 represents comparison between experimental results of pressure drop, ΔP and that calculated using correlations. Two correlations were considered: Petukhov correlation [4] and this study correlation.

It is clear from the Figure that ΔP values of this study correlation agree with both the experimental results and those calculated using Petukhovs correlation. The agreement of each one of the correlation with the experimental results reached about 0.92 for this study results and about 0.91 for Colburn results.

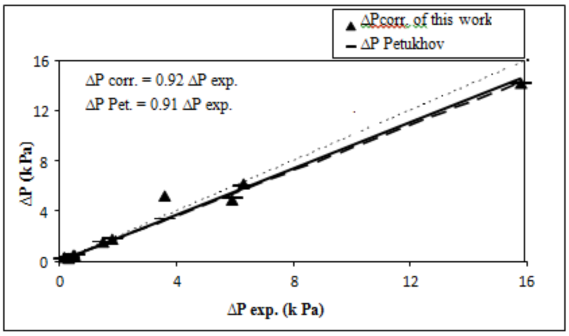

Figure 5: Experimental pressure drop, ΔP exp.Vs two correlation calculated values a) Using Petukhovs correlation, b) Using this work correlation.

Figure 6 represents comparison between experimental results of Euler number, Eu and that calculated for the correlations. Two correlations were considered: Petukhov correlation and this study correlation. Petukhov published a correlation for the friction factor, f, which relates f with Re. (equation 8), while this work formulated a correlation that connected Eu, ($\Delta P/\rho V$^2) to Re, and L/D, (equation 14).

It is clear from the Figure that Eu values of this study correlation agree with both the experimental results and those calculated using Petukhovs correlation. The agreement of each one of the correlation with the experimental results reached about 0.97 for this study results and about 0.94 for Colburn results.

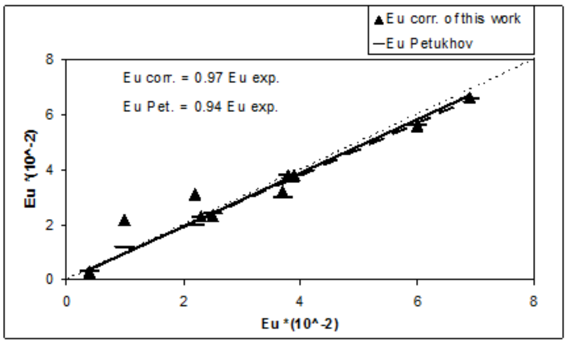

Figure 6: Experimental Euler number, Eu exp.Vs two correlation calculated values a) Using Petukhovs correlation, b) Using this work correlation.

5. Conclusions

- Simple and easy to use correlations were formulated in this study; one is related to the Nusselt number for convection heat transfer coefficient calculations. The other is related to Euler number for pressure drop calculations.
- For both h_{in} and Nu, the values of this work correlation agree with both the experimental results and those calculated using literature correlation of Colburn [4]. The agreement reaches around 0.94 with the experimental results and around 0.9 with Colburn results.
- The agreement of this work correlation in h_{in} is about 9% better than that of Colburn.
- For both ΔP and Eu, the values of this work correlation agree with both the experimental results and those calculated using Petukhovs correlation [4]. The agreement exceeds 95% in most cases.
- Petukhov correlation was for the friction factor, *f*, which relates *f* with Re. (equation 8), while this study formulated a correlation that connected Eu, ($\Delta P/\rho V^2$) to Re, and L/D, (equation 14), It is clear that this study correlation is in more agreement to the experimental results of at least 3%."
- Table 5 shows the resulting correlations for calculating heat transfer coefficient and pressure drop for single phase flow inside mini and micro tubes.

Table 5: The resulted correlations.

No.	conditions	General form, correlation	CO_2 correlation.
1-	Heat transfer	$Nu = C\,Re_D^{m}\,Pr^{n}$	$Nu = 0.24\,Re_D^{0.53}\,Pr^{0.43}$
2-	Pressure drop	$Eu = C\,(ReD^{m}\,(L/D)^{n}$	$Eu = 1.1 * 10^{-4}\,(Re_D)^{-0.26}\,(L/D)^{1.06}$

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