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STEADY STATE HEAT TRANSFER MODELS OF CO₂ CONDENSING IN A VERTICAL U-TUBE

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ABSTRACT

Two distinct steady state models have been programmed to calculate heat transfer and pressure loss from a saturated CO₂ vapor in a vertical U-tube to the surrounding grout and earth. The work began with calculations of the individual heat transfer coefficients from vapor, from the condensing vapor, and from the liquid to the tube, and then from the U-tube to the surrounding grout and earth. According to computations for the tube to the earth reviewed in the ASHARE Handbook and relevant literature on the coefficients inside the tube, all reviewed in the paper, the internal heat transfer coefficient area products, hA, for CO₂ condensing in a 3/4 inch tube diameter are much higher than the ground heat transfer coefficient; the ground heat transfer coefficient limits the heat transfer in the U-tube.

A homogeneous model assumed that the vapor-liquid mixture in the tube is represented by a fluid whose properties and heat transfer coefficients are a weighted average between those of the vapor and the liquid present at the point. The homogeneous model has been developed by the mass balance, momentum balance, energy balance, enthalpy property, equation of state, and phase equilibrium of liquid and vapor CO₂. The equations of the model have been numerically calculated in Matlab by solver ODE4 (Runge-Kutta).

Measured values of heat transfer were closed to values calculated by the model. Measurements of the pressure loss over the U-tube were significantly higher than those predicted by the model. Based on the assumption that the pressure

differences in the U-tube between the inlet and outlet are mainly due to the presence of liquid CO₂ in the up and down legs, a new simplified model has been created and the simulation results have been compared with the experimental results. Greater agreement between measured and predicted pressure losses was achieved. This study is useful in understanding heat transfer and pressure loss of CO₂ condensing in a vertical U-tube transferring heat to the earth.

KEYWORDS:

CO₂ Condensing, Homogeneous Model, Simplified Model, Measurements

INTRODUCTION

Carbon Dioxide, CO₂, is a non-flammable and non-toxic natural fluid. It has zero (0) Ozone Depleting Potential (ODP) and one (1) Global Warming Potential (GWP). These properties make CO₂ a primary candidate for the next generation environmental refrigerant. The development of CO₂ as the refrigerant is a hot topic and its application ranges from automobile air-conditioning, residential air conditioning to heat pumps [1]. In this paper, two distinct steady state models have been programmed to calculate heat transfer and pressure loss from a saturated CO₂ vapor condensing in a vertical U-tube to the surrounding grout and earth. CO₂ heat transfer coefficients are studied by numerous researchers in the world. S.M.Liao and T.S.Zhao (2002) [2] investigated heat transfer from supercritical carbon dioxide flowing in horizontal mini/micro circular tubes cooled at a constant

temperature. Six stainless steel circular tubes having inside-diameters of 0.50 mm, 0.70 mm, 1.10 mm, 1.40 mm, 1.55 mm, and 2.16 mm were tested. The heat transfer coefficient of CO₂ under different testing conditions lies from 1,000 to 5,000 W/m²-K. Chang Yong Park, et al (2009) [3] investigated the CO₂ flow condensation heat transfer coefficients and pressure drop are investigated for 0.89 mm micro channels at horizontal flow conditions, and the heat transfer of CO₂ condensing at different conditions ranges from 2,000 W/m²-K to 10,000 W/m²-K. Those literature reviews show tremendous interests in academy regarding to horizontal CO₂ condensing, but the CO₂ condensing behavior in vertical U-tube has not been studied thoroughly. In this paper, the authors investigated the CO₂ condensing properties in vertical U-tube in experiment and confirmed by the two distinct steady state models. This paper is helpful for researchers to understand CO₂ vertical condensing behavior and predict it by using models.

NOMENCLATURE

For homogenous model

P: pressure, Pa

T: temperature, °K

U: overall heat transfer coefficient from CO₂ to ground, W/m²-K

h: enthalpy, kJ/kg

u: velocity of stream in tube, m/s

z: fraction of vapor in CO₂ stream

ρ: density, kg/m³

f: fanning friction factor 0.0045

For simplified model

Q: the heat transfer capacity of the bore hole, BTU/hr

L: the borehole depth, (300ft, 91.44 m)

l: the depth of penetration of the CO₂ vapor flow into the bore hole tube at a given vapor flow m, ft

(UπD): the “thermal conductivity” of the grout and earth of the bore hole provided by ASHRAE for various compositions. The authors have used 0.74 BTU/h-ft-F (1.28 W/m-K) performance. Since this is an average value and this simplified model only use one leg to damp the heat, so the authors predicted the value should be 1.48 BTU/h-ft-F (2.56 W/m-K) in the long term operation.

ΔT: the temperature difference between the CO₂ in the bore hole and the earth surrounding it at a distance, 16 °F. (69 °F-53 °F)

m: the mass flow of CO₂ vapor to the well

ΔH: the heat of condensation of the CO₂ vapor at its temperature in the well, 65.4 BTU/lb

ΔP: the pressure drop over the well due to the static pressure of the CO₂ liquid, lbf/ft²

ρ: density of the CO₂ liquid, 49.3 lb/ft³

g: unit conversion factor for pressure equation, lbf/lb

EXPERIMENTAL SETUP

An experiment is set up for this investigation, as shown in Figure 1. The depth of the stainless steel piping is 300 ft (91.44m) to the ground with the outer diameter ¾ inch (1.9cm). Two pressure gauges are installed in the inlet and outlet of the U-tube to measure the pressures and differential pressure, together with two thermal couples. A mass flow rate meter is installed in the inlet of the U-tube. This paper is dedicated for a CO₂ model establishment and simulation, the detailed measurement data and uncertainty will not be discussed in this paper due to contract limitation.

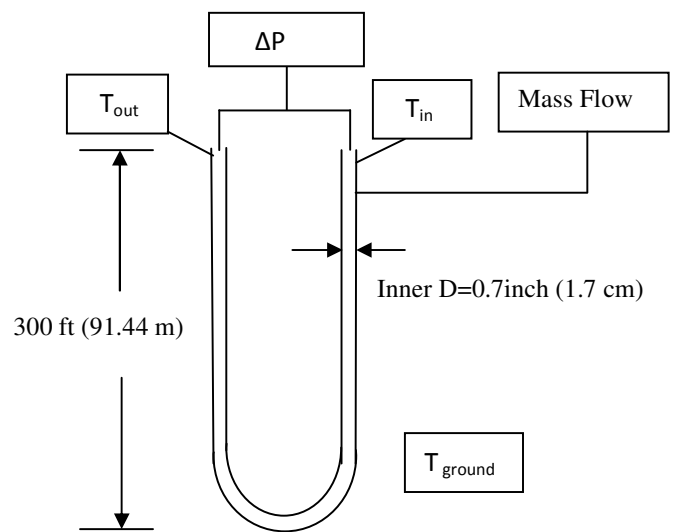


Figure 1 Experimental Setup

STEADY STATE HEAT TRANSFER COEFFICIENT

In order to simplify the heat transfer model in CO₂ condensing from vapor CO₂ to the ground in simulation, the heat transfer limiting point has been analyzed. In 2008 ASHRAE Handbook [4], the soil properties are sited based on (Kavanaugh, Rafferty, 1997) [5], the soil/rock heat conductivities range from 0.3 -2.2 BTU/ h-ft-F, in this analysis, an average 1.4BTU/h-ft-F (2.42 W/m-K) is taken. From previous literature review, the internal heat transfer coefficient area products, hA, for CO₂ condensing in a ¾ inch (1.9 cm) tube diameter ranges from 59.66 W/m-k to 596.6 W/m-k, which are much higher than the ground heat transfer coefficient (2.42 W/m-K), thus the ground heat transfer coefficient limits the heat transfer in the U-tube. So the internal heat transfer coefficient for CO₂ condensing in a U-tube in ground is ignored in the models for simplification.

MODEL ASSUMPTIONS

- 1) The CO₂ mixture is in its phase equilibrium all through the U-tube pipe;
- 2) The ground temperature is at a constant temperature 53°F (11.7 °C).

STEADY STATE HOMOGENEOUS MODEL

The flow and heat transfer can be determined by six variables in the model: Pressure (P), Temperature (T), Density (ρ), Enthalpy (h), Velocity (u) and Vapor fraction (Z). (Please refer to Nomenclature for details). So the authors need six equations to predict the condensing behavior. Take a homogeneous block $dX \cdot (\pi D^2)/4$, as shown in Figure 2 for analysis. The mass balance, momentum balance, energy balance, homogeneous enthalpy, equation of state and phase equilibrium can be applied to this homogeneous block as six governing equations. The equations are shown as below:

Mass Balance

$$\frac{\partial(\rho u)}{\partial x} = 0: \rho u = \text{constant} \quad (1)$$

Momentum Balance

$$\frac{\partial P}{\partial x} + \frac{\partial(\rho u^2)}{\partial x} - \rho g + 2f \rho u^2 / d = 0 \quad (\text{down flow}) \quad (2)$$

$$\frac{\partial P}{\partial x} + \frac{\partial(\rho u^2)}{\partial x} + \rho g + 2f \rho u^2 / d = 0 \quad (\text{up flow}) \quad (2)$$

Energy Balance

$$\frac{\partial q}{\partial x} = u A \rho \frac{\partial}{\partial x} (h + u^2/2 + gx) \quad (3)$$

$$\frac{\partial q}{\partial x} = U \pi d (T - T_{\text{ground}}) \quad (3)$$

Enthalpy

$$h = f1(P, T, \rho, z): \quad (4)$$

$$h_v = h_{v,0} + C_{p,v}(T - T_0), \quad z=1 \quad (4)$$

$$h_l = h_{l,0} + C_{p,l}(T - T_0), \quad z=0 \quad (4)$$

$$h = z h_v + (1-z) h_l, \quad 0 < z < 1 \quad (4)$$

Equation of State

$$f2(P, T, \rho, z) = 0: \quad (5)$$

$$P / \rho_v \sim RT / M_{CO_2}, \quad z=1 \quad (5)$$

$$\rho_l \sim \text{constant}, \quad z=0 \quad (5)$$

$$1/\rho = z/\rho_v + (1-z)/\rho_l, \quad 0 < z < 1 \quad (5)$$

Phase Equilibrium ($0 < z < 1$)

$$f3(P, T) = 0 \quad (6)$$

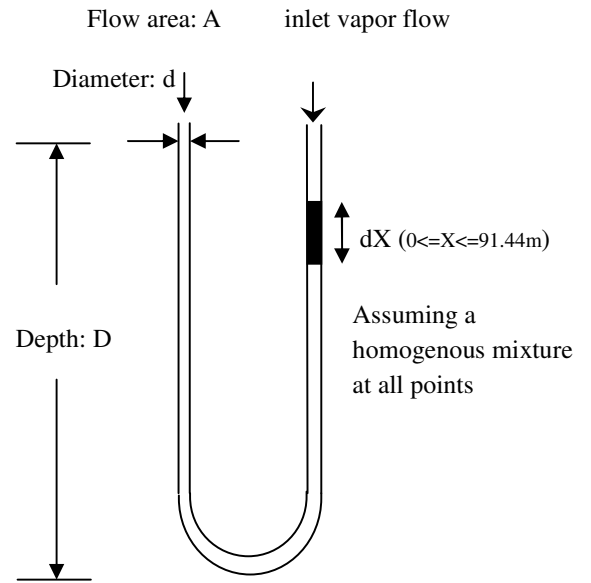


Figure 2 Homogenous Flow Model

HOMOGENEOUS MODEL INITIAL CONDITIONS

The initial conditions are obtained from experimental setup. In the experiment, $T_0 = 68.98^\circ\text{F} = 293.69^\circ\text{K} = 20.54^\circ\text{C}$ for the inlet temperature, with $P_0 = 5802378$ (Pascal) (saturation pressure at 20.54°C), $\rho_0 = 198.54$ (kg/m^3) (vapor density at 20.54°C), and $h_0 = 406.7$ (kJ/kg) (vapor enthalpy at 20.54°C) The vapor CO_2 velocity is $u_0 = 0.27$ (m/s) and Vapor fraction is $z_0 = 1$. The ground temperature is $T_{\text{ground}} = 284^\circ\text{K} = 53^\circ\text{F} = 11^\circ\text{C}$. $U \pi d = 2.42/2 = 1.21$ $\text{W}/\text{m}^2\text{-K}$ (only half the tube surrounding area is effective heat transfer area).

FORMATTING EQUATIONS TO ORDINARY DIFFERENTIAL EQUATIONS

In order to program the six equations into Matlab, the equations have to be written into the ordinary differential equation format:

Mass balance

$$\frac{\partial(\rho u)}{\partial x} = 0 \Rightarrow \rho u = \text{constant} = u_0 \rho_0 \quad (7)$$

Momentum Balance

$$\frac{\partial P}{\partial x} + \frac{\partial(\rho u^2)}{\partial x} - \rho g + 2f\rho u^2/d = 0 \text{ (down flow)}$$

$$\Rightarrow \frac{\partial u}{\partial x} = - (1/u_0\rho_0) \frac{\partial P}{\partial x} + g/u - (2f/d)*u \quad (8)$$

and define $M = u_0\rho_0$, $N = 2f/d$

Energy Balance

$$\frac{\partial q}{\partial x} = uA\rho \frac{\partial}{\partial x}(h + u^2/2 + gx)$$

$$\frac{\partial q}{\partial x} = U\pi d (T - T_{\text{ground}})$$

$$\Rightarrow \frac{\partial h}{\partial x} = -u \frac{\partial u}{\partial x} / 1000 - g/1000 + (U\pi d/uA\rho)*T_{\text{ground}} - (U\pi d/uA\rho)*T \quad (9)$$

and define $J = U\pi d/uA\rho$,
 $S = g/1000 - (U\pi d/uA\rho)*T_{\text{ground}}$

Enthalpy

$$h = f1(P, T, \rho, z):$$

$$h_v = h_{v,0} + C_{p,v}(T - T_0), z=1;$$

$$h_l = h_{l,0} + C_{p,l}(T - T_0), z=0;$$

$$h = zh_v + (1-z)h_l, 0 < z < 1$$

$$\Rightarrow \frac{\partial T}{\partial x} = \frac{1}{B*z + C_{p,l}} * \frac{\partial h}{\partial x} - \frac{B*T + A}{B*z + C_{p,l}} * \frac{\partial z}{\partial x} \quad (10)$$

and define $A = h_{v,0} - C_{p,v}T_0 + C_{p,l}T_0 - h_{l,0}$
 $B = C_{p,v} - C_{p,l}$

Equation of State

$$f2(P, T, \rho, z) = 0:$$

$$P/\rho_v \sim RT/M_{CO_2}, z=1;$$

$$\frac{\partial z}{\partial x} = \frac{(C*u*\frac{\partial u}{\partial x} + C*u*\frac{\partial P}{\partial x} - \frac{\partial P}{\partial x})*(DT - P) - (C*u*P - P)*(D*\frac{\partial T}{\partial x} - \frac{\partial P}{\partial x})}{(DT - P)^2} \quad (11)$$

define $C = F/M$, $D = F*E$,
 $E = 104.6506 \text{ ((Pa*m}^3\text{)/(K*kg))}$,
 $F = \rho l = 793.8 \text{ (kg/m}^3\text{)}$

Phase Equilibrium ($0 < z < 1$)

$$f3(P, T) = 0$$

Phase equilibrium is obtained from 2009 ASHARE Fundamental [6], by applying a regression analysis for pressure and temperature, with $R^2 = 0.998$ as shown in Figure 3. Pressure in Pa and Temperature in °K

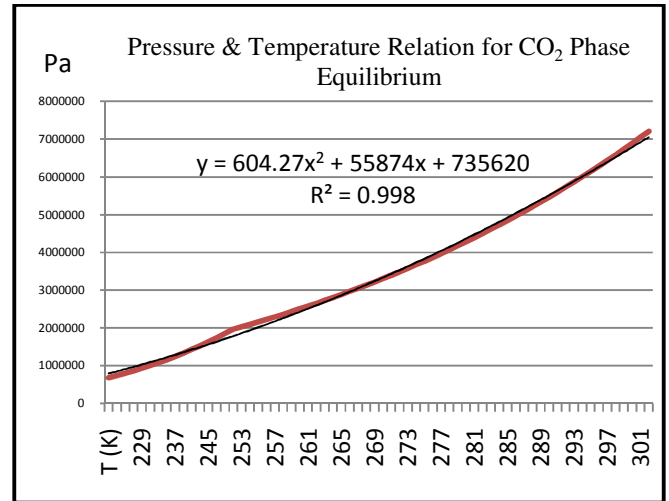


Figure 3 Regressions for Pressure and Temperature in Phase Equilibrium

So

$$\frac{\partial P}{\partial x} = 1208*T*\frac{\partial T}{\partial x} + 55874*\frac{\partial T}{\partial x} \quad (12)$$

To sum up, the six governing equations are:

$$u\rho = \text{constant} = u_0\rho_0 \quad (7)$$

$$\frac{\partial u}{\partial x} = - (1/u_0\rho_0) \frac{\partial P}{\partial x} + g/u - (2f/d)*u \text{ (down flow)} \quad (8)$$

$$\frac{\partial h}{\partial x} = -u \frac{\partial u}{\partial x} / 1000 - g / 1000 + (U \pi d / u A \rho) * T_{\text{ground}} - (U \pi d / u A \rho) * T \quad (9)$$

$$\frac{\partial T}{\partial x} = \frac{1}{B * z + C_{pl}} * \frac{\partial h}{\partial x} - \frac{B * T + A}{B * z + C_{pl}} * \frac{\partial z}{\partial x} \quad (10)$$

$$\frac{\partial z}{\partial x} = \frac{(C * P * \frac{\partial u}{\partial x} + C * u * \frac{\partial P}{\partial x} - \frac{\partial P}{\partial x}) * (DT - P) - (C * u * P - P) * (D * \frac{\partial T}{\partial x} - \frac{\partial P}{\partial x})}{(DT - P)^2} \quad (11)$$

$$\frac{\partial P}{\partial x} = 1208 * T * \frac{\partial T}{\partial x} + 55874 * \frac{\partial T}{\partial x} \quad (12)$$

Those six equations are programmed in Matlab and solved by solver ODE4 (Runge-Kutta). The results and discussions are presented in the following paragraph.

HOMOGENEOUS MODEL SIMULATION RESULTS FOR FULLY CONDENSING

The Vapor fraction (Z) distribution, Temperature (T) distribution, homogeneous enthalpy distribution (h) and pressure distribution (P) are presented in the following Figures:

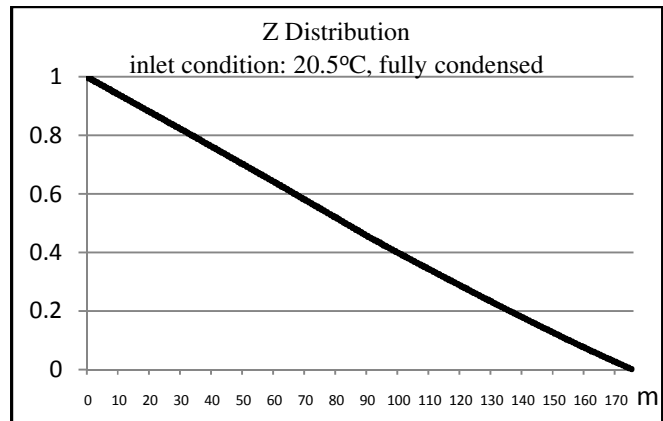


Figure 4 Vapor fraction distributions (down and up legs)

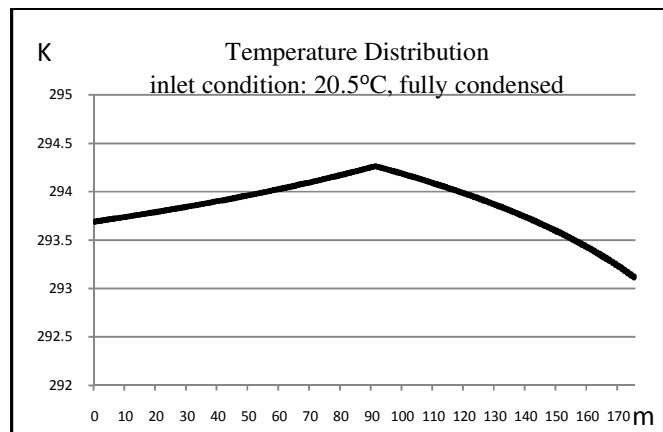


Figure 5 Temperature distributions (down and up legs)

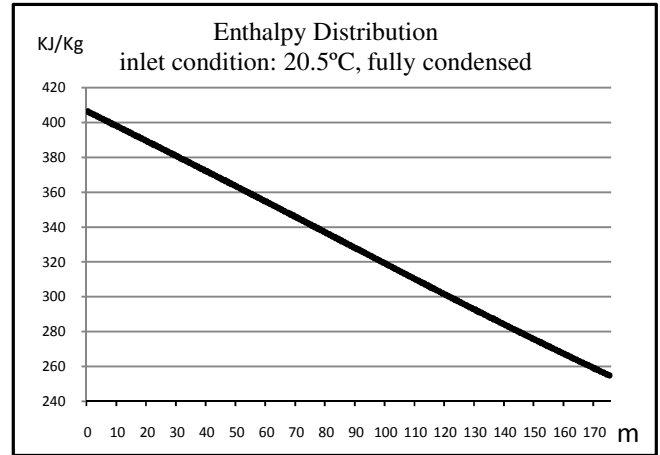


Figure 6 Enthalpy distributions (down and up legs)

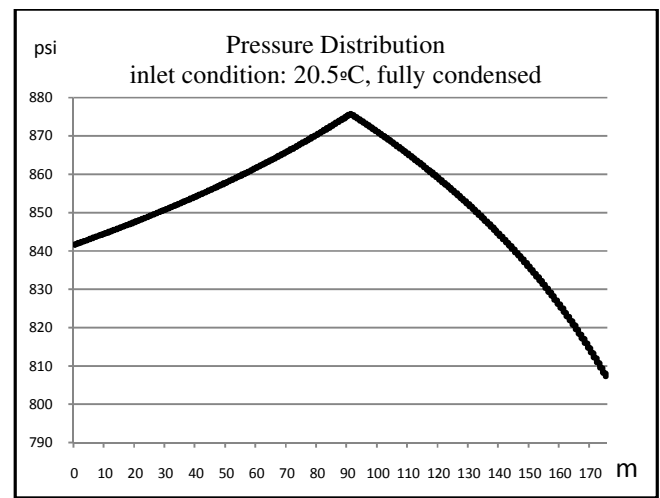


Figure 7 Pressure distributions (down and up legs)

This set of simulation shows the CO₂ condensing properties in vertical U-tube down and up legs by assuming a fully condensing from inlet to the outlet of the U-tube in the ground. Vapor fraction drops from saturated vapor (Z=1) to saturated liquid (Z=0). Assuming a phase equilibrium condition for this steady state flow, the temperature increases in the down leg due to static pressure increases as indicated in Figure 3, 5 and 7. So that's the reason in Figure 5 and 7, there is a peak at the bottom of the U-tube. At this point, the static pressure reaches its highest point and so does the temperature, assuming the CO₂ mixture is in phase equilibrium all along the tube.

The temperature measurements for inlet and outlet are 68.98 F (20.54 °C=293.69 °K) and 62.5 °F (16.9 °C = 289.9 °K). In simulation, the outlet temperature is 293 °K, this 3.1 °K temperature difference from simulation to measurement can be explained that in the measurement, the CO₂ temperature in the up leg is sub cooled by the ground, but in simulation, the authors only assume the fully condensing situation.

At the same time, the pressure measurement for inlet and outlet is 842.74 psia and 786.1 psia. In simulation, the outlet pressure is 805 psia. The pressure drop in the simulation is 35

psia compared to the measurement 56.64 psia. A lower value in simulation can be explained that the static pressure increasing in the down leg in homogeneous flow does not reflect the reality. In fact, the condensing liquid forms a thin film in an annular flow around the inner U-tube, thus the pressure increasing in the down leg would be less than homogeneous flow model prediction. So the pressure drop in reality should be higher than that predict in homogenous model.

STEADY STATE SIMPLIFIED MODEL

Based on the assumption that the pressure differences in the U-tube between the inlet to outlet are mainly due to the presence of liquid CO₂ in the up and down legs, a new simplified model has been created and the simulation results have been compared with the experimental results.

SIMPLIFIED MODEL SET UP

The simplified model is shown in Figure 8 to analyze the pressure drop and heat transfer in the U-tube.

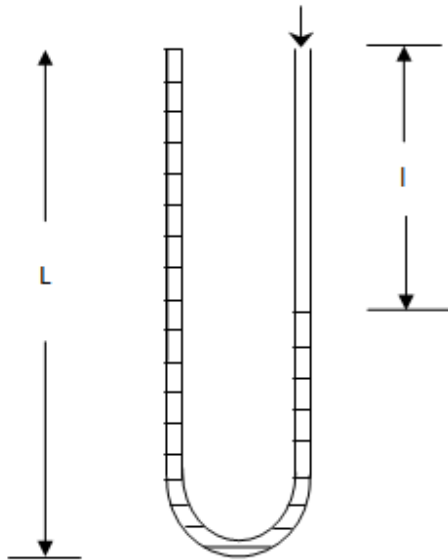


Figure 8 Simplified Model

Pressure Drop due to presence of liquid CO₂ in the up and down legs

$$\Delta P = \rho g l \quad (13)$$

Heat transfer in the down legs

$$Q = 1 (U\pi D) \Delta T = m \Delta H \quad (14)$$

Please refer to nomenclature for detailed symbol representations.

This model gives the authors opportunity to do a reverse calculation based on known experimental data. The pressure difference from inlet to outlet is 56 psi, which determines l , the depth of penetration of the CO₂ vapor flow into the bore hole tube at a given vapor flow. Based on $\Delta P = 56$ psi, the l equals 172.26 ft (52.5 m) from equation 13.

In the experiment, one also knows the mass flow rate is 0.925 kg/min. ΔH is the heat of condensation of the CO₂ vapor at its temperature in the well, 65.4 BTU/lb. ΔT is the temperature difference between the CO₂ in the bore hole and the earth surrounding it at a distance, 16 °F. (69 °F-53 °F). So the heat transfer coefficient ($U\pi D$) can be determined from equation 14. ($U\pi D$) is 2.89 BTU/h-ft-F. It is larger than the ASHRAE values, homogenous model $U\pi D=1.4$ BTU/h-ft-F. This is presumably because the well is in the early stage of operation before the surrounding earth temperatures reach “steady state” values. Based on Carslaw and Jaeger [7], the heat conductivity in solid in the long term operation will be half the heat conductivity in solid in the short term operation. The 1.4 BTU/h-ft-F picked from ASHRAE Handbook is correct, and the simplified model matches the measurements.

CONCLUSION

In the paper, two distinct steady state models have been programmed to calculate heat transfer and pressure loss from a saturated CO₂ vapor in a vertical U-tube to the surrounding grout and earth. Both models assume the ground heat transfer coefficient is the heat transfer limiting point and ignore the CO₂ internal heat transfer coefficient for simplification.

The homogeneous model has been developed by the mass balance, momentum balance, energy balance, enthalpy property, equation of state, and phase equilibrium of liquid and vapor CO₂. The equations of the model have been numerically calculated in Matlab by solver ODE4 (Runge-Kutta). The pressure predicting in homogeneous model has big error compared with measurements. In fact, the condensing liquid forms a thin film in an annular flow around the inner U-tube. This two phase flow rather than homogenous flow indicates the pressure increasing in the U-tube down leg would be less as predicted in the homogenous flow.

A simplified model is also presented to analyze the mass flow rate and pressure drop in the U-tube by assuming the pressure loss in the system mainly due to the presence of liquid CO₂ in the up and down legs. Greater agreement between measured and predicted pressure losses was achieved.

This study is dedicated to CO₂ condensing model establishment and simulation. It is useful in understanding the heat transfer and pressure loss of CO₂ condensing in a vertical U-tube transferring heat to the earth.

ACKNOWLEDGMENTS

The co-author, Dr. David H. Archer passed away in June 2010 when this paper was under review. As a member in U.S. Academy of Engineering, a professor in Department of Mechanical Engineering, Carnegie Mellon University, Dr. Archer's dedication to his work and caring about his students, strength of will, spirit and strong faith will never be forgotten. Thanks for his work and guidance in this paper.

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ANNEX A

THERMOPHYSICAL PROPERTIES OF CARBON DIOXIDE REFRIGERANT [6]

Refrigerant 744 (Carbon Dioxide) Properties of Saturated Liquid and Saturated Vapor

Temp., ^a °C	Pres- sure, MPa	Density, kg/m ³		Enthalpy, kJ/kg		Entropy, kJ/(kg·K)		Specific Heat c_p , kJ/(kg·K)			Velocity of Sound, m/s		Viscosity, $\mu\text{Pa}\cdot\text{s}$		Thermal Cond., mW/(m·K)		Surface Tension, mN/m	Temp., ^a °C
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor	c_p/c_v	Liquid	Vapor	Liquid	Vapor	Liquid		
-5.00	3.04590	956.2	0.01200	188.05	433.38	0.9576	1.8725	2.408	1.663	1.979	582	214.7	108.4	14.30	116.5	18.17	5.50	-5.00
-4.00	3.13030	950.6	0.01162	190.40	432.95	0.9660	1.8672	2.432	1.699	2.007	573	214.2	106.6	14.39	115.3	18.44	5.30	-4.00
-3.00	3.21640	945.0	0.01126	192.77	432.48	0.9744	1.8618	2.457	1.737	2.037	564	213.7	104.8	14.48	114.1	18.73	5.11	-3.00
-2.00	3.30420	939.2	0.01091	195.16	431.99	0.9829	1.8563	2.484	1.777	2.068	555	213.1	102.9	14.58	112.9	19.03	4.92	-2.00
-1.00	3.39380	933.4	0.01057	197.57	431.46	0.9914	1.8509	2.512	1.819	2.102	546	212.6	101.2	14.68	111.6	19.34	4.73	-1.00
0.00	3.48510	927.4	0.01024	200.00	430.89	1.0000	1.8453	2.542	1.865	2.138	536	212.0	99.4	14.79	110.4	19.67	4.54	0.00
1.00	3.57830	921.4	0.00992	202.45	430.29	1.0086	1.8397	2.574	1.913	2.176	527	211.5	97.6	14.89	109.2	20.02	4.35	1.00
2.00	3.67330	915.2	0.00961	204.93	429.65	1.0172	1.8340	2.609	1.965	2.218	518	210.9	95.9	15.00	108.0	20.38	4.17	2.00
3.00	3.77010	909.0	0.00931	207.43	428.97	1.0259	1.8282	2.645	2.020	2.262	508	210.3	94.2	15.12	106.8	20.76	3.99	3.00
4.00	3.86880	902.6	0.00901	209.95	428.25	1.0346	1.8223	2.685	2.080	2.309	499	209.6	92.5	15.24	105.5	21.17	3.80	4.00
5.00	3.96950	896.0	0.00872	212.50	427.48	1.0434	1.8163	2.727	2.144	2.360	489	209.0	90.8	15.36	104.3	21.60	3.62	5.00
6.00	4.07200	889.4	0.00845	215.08	426.67	1.0523	1.8102	2.772	2.213	2.416	480	208.3	89.1	15.49	103.1	22.06	3.45	6.00
7.00	4.17650	882.6	0.00817	217.69	425.81	1.0612	1.8041	2.822	2.289	2.476	470	207.6	87.5	15.62	101.8	22.54	3.27	7.00
8.00	4.28310	875.6	0.00791	220.34	424.89	1.0702	1.7977	2.875	2.370	2.541	460	206.9	85.8	15.76	100.6	23.06	3.10	8.00
9.00	4.39160	868.4	0.00765	223.01	423.92	1.0792	1.7913	2.934	2.460	2.612	451	206.2	84.2	15.91	99.4	23.61	2.93	9.00
10.00	4.50220	861.1	0.00740	225.73	422.88	1.0884	1.7847	2.998	2.558	2.690	441	205.4	82.6	16.06	98.1	24.21	2.76	10.00
11.00	4.61490	853.6	0.00715	228.49	421.79	1.0976	1.7779	3.068	2.666	2.776	431	204.6	80.9	16.22	96.9	24.84	2.59	11.00
12.00	4.72970	845.9	0.00691	231.29	420.62	1.1070	1.7710	3.145	2.786	2.871	421	203.8	79.3	16.39	95.6	25.53	2.42	12.00
13.00	4.84660	837.9	0.00668	234.13	419.37	1.1165	1.7638	3.232	2.919	2.977	411	203.0	77.7	16.56	94.4	26.27	2.26	13.00
14.00	4.96580	829.7	0.00645	237.03	418.05	1.1261	1.7565	3.328	3.068	3.095	401	202.1	76.1	16.75	93.1	27.08	2.10	14.00
15.00	5.08701	821.2	0.00622	239.99	416.64	1.1359	1.7489	3.436	3.237	3.228	391	201.2	74.4	16.95	91.9	27.96	1.95	15.00
16.00	5.21080	812.4	0.00600	243.01	415.12	1.1458	1.7411	3.558	3.429	3.378	381	200.3	72.8	17.16	90.6	28.93	1.79	16.00
17.00	5.33680	803.3	0.00578	246.10	413.50	1.1559	1.7329	3.698	3.649	3.550	370	199.3	71.2	17.39	89.4	29.99	1.64	17.00
18.00	5.46510	793.8	0.00557	249.26	411.76	1.1663	1.7244	3.858	3.905	3.748	360	198.3	69.5	17.64	88.1	31.16	1.49	18.00
19.00	5.59580	783.8	0.00536	252.52	409.89	1.1769	1.7155	4.044	4.204	3.979	349	197.2	67.8	17.90	86.9	32.47	1.35	19.00
20.00	5.72910	773.4	0.00515	255.87	407.87	1.1877	1.7062	4.264	4.560	4.252	338	196.1	66.1	18.19	85.7	33.94	1.20	20.00
21.00	5.86480	762.4	0.00494	259.33	405.67	1.1989	1.6964	4.526	4.990	4.578	326	194.9	64.4	18.50	84.5	35.61	1.06	21.00
22.00	6.00310	750.8	0.00474	262.93	403.26	1.2105	1.6860	4.846	5.519	4.976	314	193.6	62.7	18.85	83.4	37.52	0.93	22.00
23.00	6.14400	738.4	0.00453	266.68	400.63	1.2225	1.6749	5.248	6.185	5.472	302	192.3	60.9	19.23	82.4	39.74	0.80	23.00
24.00	6.28770	725.0	0.00433	270.61	397.70	1.2352	1.6629	5.767	7.049	6.107	288	190.8	59.0	19.66	81.5	42.35	0.67	24.00
25.00	6.43420	710.5	0.00412	274.78	394.43	1.2485	1.6498	6.467	8.212	6.949	274	189.1	57.0	20.16	80.8	45.51	0.55	25.00
26.00	6.58370	694.5	0.00391	279.26	390.71	1.2627	1.6353	7.460	9.862	8.121	259	187.2	55.0	20.73	80.5	49.44	0.44	26.00
27.00	6.73610	676.4	0.00369	284.14	386.39	1.2783	1.6189	8.970	12.38	9.870	243	185.0	52.8	21.42	80.7	54.56	0.33	27.00
28.00	6.89180	655.3	0.00346	289.62	381.20	1.2958	1.5999	11.550	16.69	12.780	225	182.1	50.3	22.27	81.9	61.73	0.23	28.00
29.00	7.05090	629.4	0.00320	296.07	374.61	1.3163	1.5763	16.950	25.74	18.630	205	178.2	47.5	23.41	85.2	73.19	0.13	29.00
30.00	7.21370	593.3	0.00290	304.55	365.13	1.3435	1.5433	35.340	55.82	36.660	177	171.3	43.8	25.17	95.4	98.02	0.05	30.00
30.98 ^c	7.37730	467.6	0.00214	332.25	332.25	1.4336	1.4336	(a)	(a)	(a)	0	0.0	—	—	(a)	(a)	0.00	30.98

^aTemperatures on ITS-90 scale

^bTriple point

^cCritical point