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Materials Today: Proceedings PMME(2016) EMT–354

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PMME 2016

An Overview of Propane Based Domestic Refrigeration Systems

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Abstract

This paper reports that the volumetric and thermodynamic properties of propane has been estimated using Peng-Robinson Equation of state. The values of vapour pressure, liquid specific volume, vapour specific volume, liquid enthalpy, and vapour enthalpy have been estimated. Thermodynamic analysis of 89W domestic refrigerator is carried out. Performance parameters of propane namely, volumetric efficiency, displacement volume, discharge temperature, Refrigerating effect is calculated and it is compared with the practical results obtained from the refrigeration test rig.

Selection and Peer-review under responsibility of International Conference on Processing of Materials, Minerals and Energy (July 29th – 30th) 2016, Ongole, Andhra Pradesh, India.

Keywords: propane; COP; Compressor work input; Discharge temperature; volumetric efficiency.

1. Introduction

Refrigeration and air conditioning equipments are extensively used in many fields. In the earlier times the main refrigerants used were CFC based. Both CFCs and HCFCs were commonly used in the last few decades. Unfortunately, these kind of refrigerants seriously deplete the ozone layer and contribute to the greenhouse effect and hence some of them have been phased out and the remaining are in the process of being phased out in accordance with Montreal Protocol [1]. HFCs deemed to be suitable replacement for HCFCs and CFCs and have

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high GWP. Hence natural refrigerants such as hydrocarbons are seemed to be breaking new ground as suitable refrigerants devoid of above ills associated with commonly used refrigerants. Eric Granryd [9] analyzed theoretically and concluded that Hydrocarbons are better substitutes of R12. B.Saleh et al [10] screened pure fluids as alternatives to R12 based on back one equation of states. In this context, Propane [2] is a very interesting substitute regarding its thermodynamic efficiency, its miscibility with mineral oil, its price, availability and its negative effect on the environment. Propane is compatible with copper and also has excellent lubrication properties. Unlike propyne and propadiene which react with copper forming metal acetylides which are explosive in nature [3]. Another advantage of propane is that due to positive evaporator pressure, these systems historically have required fewer tube joint replacements due to corrosion. By nature, negative pressure systems tend to take in air, which contains moisture that mixes with the refrigerant to form acids that eventually cause corrosion problems. Heat transfer coefficients for propane is significantly higher than conventional refrigerants both in liquid and gaseous phase. Hence, propane is efficient from heat transfer perspective.

Nomenclature

C	Coefficient of performance
h	Enthalpy, [kj kg-1]
m	mass flow rate, [kg s-1]
n	Polytrophic index
P	Pressure in [pa]
Q0	Refrigeration Effect [kW]
T	Temperature [K]
v	Specific Volume [m3kg-1]
W	Power input [W]
s	Entropy [kj kg-1 K-1]
η	Efficiency
Subscripts	
c	Critical
f	Saturated liquid
g	saturated vapour
i	inlet
is	isentropic
k	condenser
n	polytropic
o	Evaporator
0,1,2 etc	State points
v	**Efficiency**

2. Generation of Thermodynamic Properties

2.1 Wagner Equation

Wagner equation provides relation between saturation pressure and saturation temperature of a substance. Wagner equation is given by

$$P = P_c * P_r \quad (1)$$

Where,

$$\text{Log } P_r = \frac{A(1-T_r)}{T_r} + \frac{B(1-T_r)^{1.5}}{T_r} + \frac{C(1-T_r)^3}{T_r} + \frac{D(1-T_r)^6}{T_r} \quad (2)$$

Here,

$$T_r = \frac{T}{T_c} \quad (3)$$

A, B, C, D are Wagner constants.

Pc and Tc are critical Pressure and Critical Temperature respectively.
For propane, the constants are listed in Table 1. [4]

Table 1: Wagner and critical values of propane

Sl No	Properties	Values
1	A	-6.687700
2	B	+1.248800
3	C	-1.974500
4	D	-2.053900
5	Pc	42.4924 bar
6	Tc	369.8 K

The program was executed in MATLAB and the readings were recorded in Table 1.2. The corresponding values of saturation temperature vs. saturation pressure are plotted as shown in Fig 2.1.

a. b.

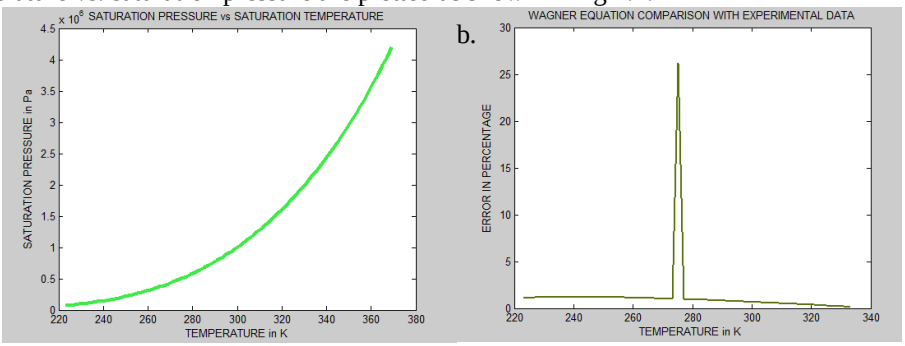

Fig 1: a) Saturation temperature vs Saturation pressure for propane
b) Wagner error percentage

These values were compared with actual experimental readings [6] and error percentage was calculated, which is shown in Fig 1 (b). Experimental Data becomes crucial in the range of temperatures where the error percentage crosses 5%.

2.2 Equations of state [6]

An equation of state is a mathematical relation between fundamental thermodynamic properties. An equation of state describes the effect of pressure on system properties such as temperature and specific volume. It is constructed by the consideration of the effect of inter molecular forces on energy and pressure of the fluid [5]. The simplest theoretical equation of state is the perfect gas equation representing the behaviour of a gas at low pressures and high temperatures.

The equation is $v^{id} = \frac{R*T}{P}$ (4)

For real gas, the actual volume can be expressed by the general relation

$$v^{real} = Z * \frac{R*T}{P} \quad (5)$$

Where, $Z = \frac{v^{real}}{v^{id}}$ is called the compressibility of the gas. One of the most influential cubic equations of state is Van der Waals equation of state. This equation employs the principle of corresponding states by considering the characteristics of microscopic and macroscopic states. The semi empherical correction to van der Waals equation is the Peng Robinson equation of state. The equation can be mathematically expressed as,

$$p = \frac{RT}{v-b} - \frac{a}{v^2+2bv-b^2} \quad (6)$$

Where,

$$a = 0.45724\frac{R^2T_c^2}{p_c}\left[1 + f(\omega)\left\{1 - \left(\frac{T}{T_c}\right)^{0.5}\right\}\right]^2 \quad (7)$$

$$b = \frac{0.0778RT_c}{p_c} \quad (8)$$

$$f(\omega) = 0.37464 + 1.54226\omega - 0.26992\omega^2 \quad (9)$$

$$\omega = -1.0 - \log(p_r^{sat})_{T_{r=0.7}} \quad (10)$$

$$T_r = \frac{T}{T_c} \text{ and } P_r = \frac{p}{p_c} \quad (11)$$

As the equation is cubic in nature, it has three roots for the equation. When calculated under critical conditions, three real roots are obtained. The maximum root is associated to the specific volume at saturated vapour and minimum value is assigned to the specific volume at saturated liquid phase.

Equation 6 is solved for propane, at fixed values of temperature and hence obtained Isotherms are plotted as shown in the Fig 2.

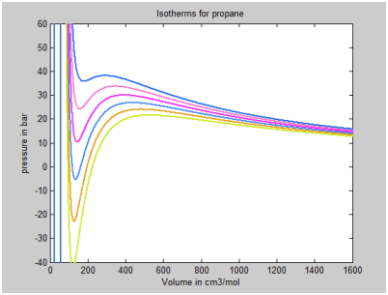

Fig 2: Isothermal lines for propane with increasing temperature

The cubic Peng – Robinson Equation of state is solved in MATLAB. Specific Volumes at saturated liquid and vapour states are tabulated for a temperature range of -260C to 60C in Table 2

Table 2: Saturated Specific volumes at different pressure and temperature

T (K)	P (Pa)	Vf (m3/kg)	Vg (m3/kg)
247.15	196507.5	0.001666	0.224016
249.15	211867.7	0.001674	0.208739
251.15	228126.0	0.001682	0.194722
253.15	245315.9	0.001691	0.181843
255.15	263470.8	0.001699	0.169993
257.15	282624.8	0.001708	0.159075
259.15	302812.2	0.001717	0.149003
261.15	324067.6	0.001726	0.139700
263.15	346426.1	0.001735	0.131096
265.15	369922.9	0.001745	0.123129
267.15	394593.8	0.001755	0.115744
269.15	420474.6	0.001765	0.108889
271.15	447601.6	0.001775	0.102520
273.15	476011.4	0.001786	0.096595
275.15	505740.9	0.001797	0.091079
277.15	536827.3	0.001809	0.085936
279.15	569308.1	0.001820	0.081138

2.3 Derived Thermodynamic Properties

Secondary thermodynamic properties such as enthalpy and entropy at saturated liquid line and saturated vapour line are calculated using Ideal gas equation of state for specific enthalpy and specific entropy in combination with departure functions [6]. A departure function indicates the deviation of the properties of the fluid from ideal gas behaviour.

Enthalpy departure for Peng-Robinson equation of state is given by

$$\frac{H-H^{ig}}{RT} = Z-1-\frac{A}{B\sqrt{8}}\left(+\frac{f(\omega)\sqrt{T_r}}{\sqrt{\alpha}}\right)\ln\left[\frac{Z+(1+\sqrt{2})B}{Z+(1-\sqrt{2})B}\right] \quad (12)$$

Where,

$$B = \frac{bP}{RT} \text{ and } A = \frac{aP}{R^2T^2}$$

Z is the compressibility factor obtained from cubic equation of state.

Entropy departure for Peng-Robinson equation of state is given by

$$\frac{S-S^{ig}}{R} = \ln(Z-B)-\frac{A}{B\sqrt{8}}\left(+\frac{f(\omega)\sqrt{T_r}}{\sqrt{\alpha}}\right)\ln\left[\frac{Z+(1+\sqrt{2})B}{Z+(1-\sqrt{2})B}\right] \quad (13)$$

Internal energy departure for Peng-Robinson equation of state is given by

$$\frac{U-U^{ig}}{RT} = -\frac{A}{B\sqrt{8}}\left(+\frac{f(\omega)\sqrt{T_r}}{\sqrt{\alpha}}\right)\ln\left[\frac{Z+(1+\sqrt{2})B}{Z+(1-\sqrt{2})B}\right] \quad (14)$$

These equations are calculated for saturation pressure and saturated temperature, results are tabulated and they are plotted against temperature as shown in the Fig 3, Fig 4 and Figure 5

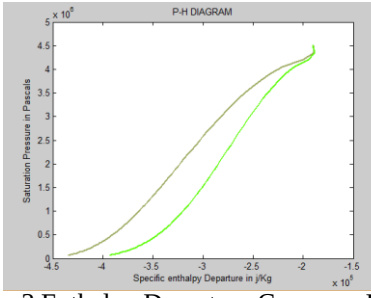

Fig 3 Enthalpy Departure Curves

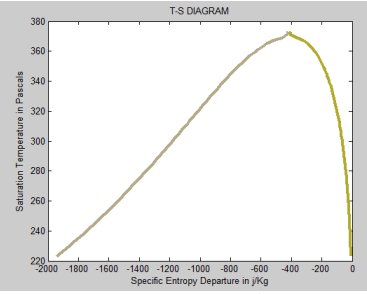

Fig 4 Entropy Departure Curves

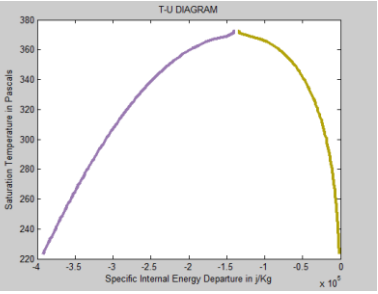

Fig 5 Internal Energy Departure Curves

By considering the reference enthalpy of 200kj/kg and reference entropy as 0 kj/kgK, thermodynamic property table for propane is generated. These generated properties are tabulated in Table 3

Table 3: Property Table for propane

T (K)	Pressure (MPa)	V_f (m^3/kg)	V_g (m^3/kg)	h_f (kj/kg)	hg (kj/kg)	S_f (kj/kgK)	S_g (kj/kgK)
248	0.20228	0.0017832	0.217120	139.25	546.11	0.76871	2.4093
253	0.24320	0.0018030	0.182590	151.01	551.96	0.81537	2.4001
258	0.29012	0.0018236	0.154570	162.92	557.75	0.86165	2.3920
263	0.34357	0.0018450	0.131650	174.98	563.48	0.90759	2.3848
268	0.40411	0.0018675	0.112740	187.22	569.14	0.95324	2.3783
273	0.47229	0.0018911	0.097042	199.62	574.7	0.99864	2.3725
278	0.54869	0.0019159	0.083911	212.22	580.16	1.04380	2.3674

3. Thermodynamic Analysis

The performance analysis of vapour compression refrigeration system is important from two point. Firstly, the efforts to find drop-in replacements for CFC based refrigerants forces us to find the compressor displacement value. Therefore when we find refrigerants that provide compressor displacement volume adjacent to the CFC based refrigerants; it means that the refrigerant can be used instead of the relevant CFC. The analysis of these systems gives us the COP of the system, which guides us when arbitrating the specification of the new systems.

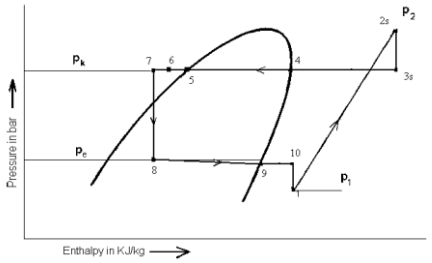

Fig. 6. Ten point Vapour compression cycle

Thermodynamic analysis is based on ten point vapour compression cycle. The ten state points are shown in the p-h diagram [5]. The ten points are specified as follows.

1. Refrigerant state in the cylinder before compression begins.
2. Refrigeration state in the cylinder after compression ends.
3. Compressor shell outlet/condenser inlet condition.
4. Saturated vapour state in the condenser at 550C.
5. Saturated liquid state in the condenser at 550C.
6. Sub cooled liquid state leaving condenser at 430C.
7. Capillary inlet condition at 320C.
8. Evaporator inlet condition/Capillary outlet at -250C.
9. Saturated vapour refrigerant state leaving evaporator.
10. State at inlet to the shell of hermetic compressor.

Pressure drops at the inlet and outlet valves of compressor for propane are assumed as follows:

a) ΔPi = 0.2bar and ΔPo = 0.4bar
b) Pressure drop in evaporator is 0.1bar and ambient temperature is 430C.

4. Evaluation of Performance Parameters

Performance parameters with propane refrigerant to obtain the same refrigerating capacity of 89W as with conventional refrigerators are calculated.

Pressure ratio, $\mathrm{Pr} = \frac{P2}{P1}$ (15)

Refrigerating effect, $q_0 = (h_9 - h_8)$ (16)

$m = \frac{\mathrm{Q_0}}{\mathrm{q_0}}$ (17)

$V_p = \frac{m v_1}{\eta_v 60N}$ (18)

$Q_k = m(h_{3s} - h_6)$ (19)

$\mathrm{COP} = \frac{\mathrm{Q_0}}{\mathrm{W_0}}$ (20)

$W_{is} = \dot{m}(h_{2s} - h_1)$ (21)

These performance parameters are evaluated over different evaporator temperatures and the results are plotted in the Fig 7

5. Conclusion

Propane can be used as an alternative for conventional refrigerants with lower displacement compressor. Because of lower mass flow rates the design of evaporator for retrofitting propane has to be modified slightly i.e., the evaporator pipes have to be constructed of small diameter pipes and also because of smaller mass flow rates smaller bore and longer capillary than that used for conventional refrigerants like R12 and R134a. The existing refrigerators of 75literes capacity have lower displacement compressors with lower motor rating can be used for propane refrigerants at the cost of slightly decreased capacity from the point of view of energy conversion. Further experimentation is required to arrive at optimum motor rating.

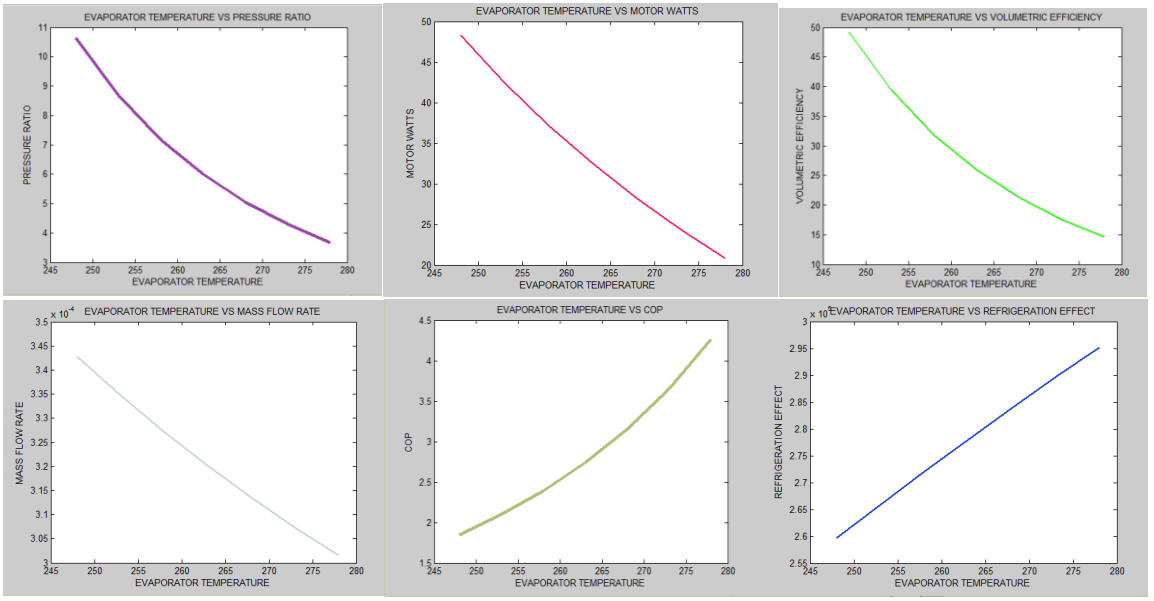

Fig 7: Variation of performance parameters of propane with evaporator temperatures

Table 4: Performance parameters of propane with variation of evaporator temperature

SL NO	Evaporator Temperature (^{0}C)	Pressure ratio	COP	Refrigeration Effect (j/Kg)	Volumetric Efficiency (%)	Mass flow rate (Kg/s)	Motor Watts (W)	Compressor displacement (cc)
1	-25	10.65	1.843	259700	49.3	3.34E-04	48.29	2.133
2	-20	8.70	2.097	265920	39.4	3.35E-04	42.45	1.706
3	-15	7.19	2.394	272030	31.8	3.27E-04	37.18	1.378
4	-10	6.00	2.742	278010	25.9	3.20E-04	32.46	1.122
5	-5	5.05	3.157	283870	21.3	3.14E-04	28.20	0.920
6	0	4.29	3.657	289620	17.6	3.07E-04	24.34	0.760
7	5	3.67	4.269	295220	14.6	3.01E-04	20.85	0.631

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