A simple approach for evaluating the performance of a refrigeration system in the natural gas processing industry

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ORIGINAL SCIENTIFIC PAPER

Refrigeration systems are common in the natural gas processing industry and processes related to the petroleum refining, petrochemical, and chemical industries. Several applications for refrigeration include natural gas liquids (NGL) recovery, liquefied petroleum gas (LPG) recovery, hydrocarbon dew point control, reflux condensation for light hydrocarbon fractionators, and liquefied natural gas (LNG) plants. In the present work, simple-to-use predictive tool is formulated to arrive at an appropriate estimation of main design parameters in three-stage propane refrigerant systems. The proposed tool is suitable for the range of evaporator temperatures between -40 °C and 60 °C and the refrigerant condensing temperatures range between 10 °C to 70 °C. Results show that the proposed predictive tool has a very good agreement with the reported data wherein the average absolute deviation percent hovered around 1.4%. The tool developed in this study can be of immense practical value for the engineers and scientists to have a quick check on the performance of propane refrigerant systems at various conditions. In particular, gas processing and chemical engineers would find the proposed approach to be user-friendly with transparent calculations involving no complex expressions.

Key words: propane; refrigeration, condenser duty, natural gas, compressor power

1. Introduction

Refrigeration systems are widely used in the natural gas processing industry and processes related to the petroleum refining, petrochemical, and chemical industries. Propane refrigeration systems are often required in the natural gas processing industry to provide the required chilling in condensing heavy components for a rich gas.[8] In this process the natural gas stream is chilled with an external propane refrigeration system, and then the condensed liquids are separated in a low temperature separator and stabilized in a column.[12] Figure 1 shows a schematic flow diagram of three-stage propane refrigeration system. Propane has zero ozone depletion potential and negligible global warming potential.[4] Propane has excellent thermodynamic properties, quite similar to those of ammonia. The molar mass of 44 is ideal for turbo compressors and is only about one third of its halocarbon competitors.[14] Propane is cheaply and universally available.[4] The major advantage of selecting propane as the refrigerant over ammonia is that propane is non-toxic.[4] However its flammability is a serious concern and hence safe design and operating practice is of paramount importance. However, this disadvantage can be eluded by using it as a refrigerant for the LT cycle.[4] It is important to note that propane can be used for very low temperature refrigeration applications (between -30 and -60 °C) compared to ammonia due to its lower NBP.[4]

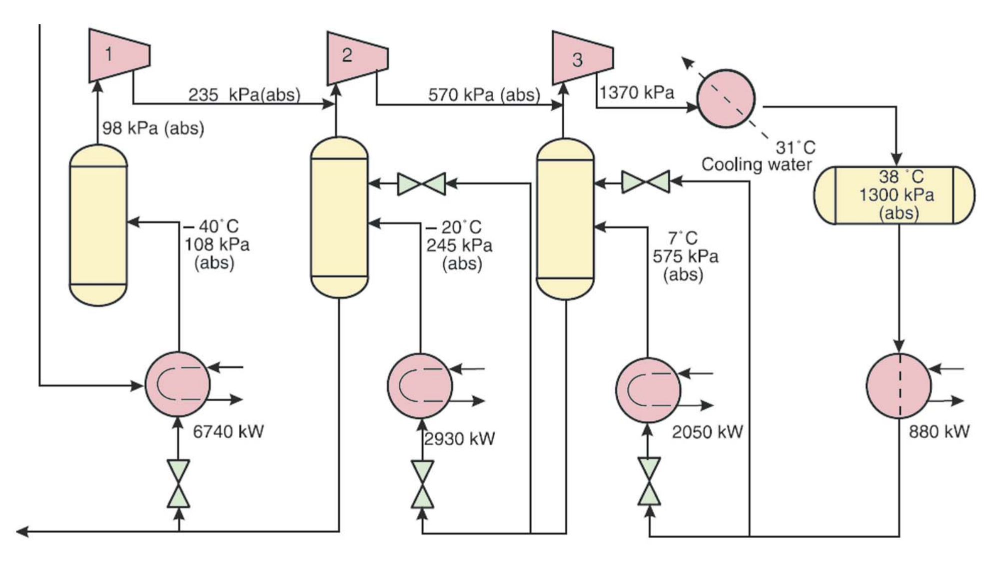

Fig. 1 Schematic flow diagram of three-stage propane refrigeration system
Sl. 1. Shematski dijagram toka trostupanjskog propanskog sustava hlađenja

There has been a strong surge in installing CO_2 based systems and a large number of research studies have been reported to highlight its extremely favorable thermodynamic and environmental properties.[11] Propane is not corrosive with many materials such as aluminium, brass, bronze, copper, stainless steel, silver etc. Therefore, it is fully compatible with existing components such as heat exchangers, expansion valves, compressors, lubricants and copper tubing which are currently used in refrigeration systems.[8]

Refrigeration systems utilizing one, two, three, or four stages of compression have been successfully operated in various services. The number of levels of refrigeration generally depends upon the number of compression stages required, interstage heat loads, economics, and the type of compression.[8] In addition environmental concerns have increased interest in using natural refrigerants such as hydrocarbons (e.g. propane, iso-butane and mixtures) as alternatives to the synthetic fluorocarbon refrigerants in a wide range of applications.[10,17,15,1,16] Generally, these studies reported significant performance and economic benefits for hydrocarbons compared with fluorocarbons. In view of the above mentioned issues, it is necessary to develop an accurate and simple method which is easier than existing approaches less complicated with fewer computations for predicting the compressor power and condenser duty per refrigeration duty in three-stage propane refrigerant systems. The paper discusses the formulation of such predictive tool in a systematic manner along with sample example to show the simplicity of the model and usefulness of such tools.

2. Methodology to develop predictive tool

Since many gas processing plants require mechanical refrigeration and because of the complexity of generalizing refrigeration systems, a predictive tool should be developed to aid in a modular approach for designing refrigeration systems. In order to apply this proposed tool to most of the commercially available compressors, a polytropic efficiency of 0.77 was assumed.[8] The polytropic efficiency was converted into an isentropic efficiency to include the effects of compression ratio and specific heat ratio ($k = C_p/C_v$) for a given refrigerant.[8] For well balanced and efficient operation of the compressor, an equal compression ratio between stages was employed.[8] The refrigeration level is defined as the temperature of the dew point vapor leaving the evaporator. The pressures at the compressor suction and side load inlet nozzles were adjusted by 10 kPa (1.45 psi) to allow for pressure drop. This tool also includes a 70 kPa (10.15 psi) pressure drop across the refrigerant condenser for propane. The proposed tool is superior due to its clear numerical background based on Vandermonde matrix, wherein the relevant coefficients can be retuned quickly for various cases.

2.1. Vandermonde matrix

Vandermonde matrix is a matrix with the terms of a geometric progression in each row, i.e., an $m \times n$ matrix.[9]

$$V = \begin{bmatrix} 1 & \alpha_1 & \alpha_1^2 & \cdots & \alpha_1^{n-1} \\ 1 & \alpha_2 & \alpha_2^2 & \cdots & \alpha_2^{n-1} \\ 1 & \alpha_3 & \alpha_3^2 & \cdots & \alpha_3^{n-1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & \alpha_m & \alpha_m^2 & \cdots & \alpha_m^{n-1} \end{bmatrix} \quad (1)$$

or

$$V_{i,j} = \alpha_i^{j-1} \quad (2)$$

for all indices i and j. The determinant of a square Vandermonde matrix (where $m=n$) can be expressed as:[9]

$$\det(V) = \prod_{1 \le i < j \le n} \left(\alpha_j - \alpha_i\right) \quad (3)$$

The Vandermonde matrix evaluates a polynomial at a set of points; formally, it transforms *coefficients* of a polynomial $a_0 + a_1x + a_2x^2 + \ldots + a_{n-1}x^{n-1}$ to the values the polynomial takes at the point's α_i. The non-vanishing of the Vandermonde determinant for distinct points α_i shows that, for distinct points, the map from coefficients to values at those points is a one-to-one correspondence, and thus that the polynomial interpolation problem is solvable with unique solution; this result is called the unisolvence theorem.[7]

They are thus useful in polynomial interpolation, since solving the system of linear equations $Vu = y$ for u with V and $m \times n$ Vandermonde matrix is equivalent to finding the coefficients u_j of the polynomial(s).[7]

$$\psi(x) = \sum_{j=0}^{n-1} u_j x^j \quad (4)$$

of degree $\le n$-1 which has (have) the property:

$$\psi(\alpha_i) = y_i \text{ for } i = 1,\ldots,m \quad (5)$$

The Vandermonde matrix can easily be inverted in terms of Lagrange basis polynomials: each *column* is the coefficients of the Lagrange basis polynomial, with terms in increasing order going down. The resulting solution to the interpolation problem is called the Lagrange polynomial.[7]

2.2. Methodology to Develop Predictive Tool

The required data to develop this predictive tool includes the compressor power and condenser duty per refrigeration duty in three-stage propane refrigerant system, evaporator temperature and refrigerant condensing temperature. In this work, the compressor power and condenser duty per refrigeration duty in three-stage propane refrigerant system is predicted rapidly by proposing a simple tool. The following methodology has been applied to develop this simple tool.[2]

Firstly, the compressor powers and condenser duties per refrigeration duty in three-stage propane refrigerant system are correlated as a function of evaporator temperature (K) for different refrigerant condensing temperature (K). Then, the calculated coefficients for these polynomials are correlated as a function of refrigerant condensing temperature. The derived polynomials are applied to calculate new coefficients for equations (6) and (7) to predict, the compressor powers and condenser duties per refrigeration duty in three-stage propane refrig-

Table 1. Tuned coefficients for equations 8 to 11

Coefficient	Values for compressor power in kW per refrigeration duty in MW	Values for condenser duty in Kw per MW of refrigerant
A_1	$-9.939\,664\,301\times10^{5}$	$-2.549\,657\,006\,0\times10^{6}$
B_1	$1.295\,718\,054\times10^{4}$	$2.718\,696\,533\,7\times10^{4}$
C_1	$-5.086\,891\,269\times10^{1}$	$-9.452\,002\,919\times10^{1}$
D_1	$6.320\,882\,307\times10^{-2}$	$1.080\,9134\,274\times10^{-1}$
A_2	$8.959\,771\,407\,9\times10^{3}$	$3.968\,894\,433\,8\times10^{4}$
B_2	$-1.256\,891\,481\,7\times10^{2}$	$-4.124\,032\,533\,9\times10^{2}$
C_2	$5.118\,715\,087\,9\times10^{-1}$	$1.406\,753\,656$
D_2	$-6.495\,788\,495\times10^{-4}$	$-1.583\,143\,379\,5\times10^{-3}$
A_3	$-2.456\,126\,126\,2\times10^{1}$	$-1.880\,150\,920\,07\times10^{2}$
B_3	$3.894\,571\,235\,4\times10^{-1}$	$1.926\,689\,16$
C_3	$-1.672\,973\,379\times10^{-3}$	$-6.502\,325\,916\,8\times10^{-6}$
D_3	$2.186\,667\,067\times10^{-6}$	$7.251\,734\,483\,4\times10^{-3}$
A_4	$1.741\,918\,922\,6\times10^{-2}$	$2.789\,872\,277\,94\times10^{-1}$
B_4	$-3.657\,081\,906\times10^{-4}$	$-2.835\,917\,751\,2\times10^{-3}$
C_4	$1.7239\,116\,599\times10^{-6}$	$9.510\,529\,773\,3\times10^{-6}$
D_4	$-2.3607\,788\,587\times10^{-9}$	$-1.054\,980\,444\,2\times10^{-8}$

erant system. Table 1 shows the tuned coefficients for equations (8) to (11) for the percent of blowdown that is flashed to steam in the design of boilers with blowdown systems according to the reliable data.[8]

In brief, the following steps[3] are repeated to tune the correlation's coefficients:

1. Correlate the compressor powers and condenser duties per refrigeration duty in three-stage propane refrigerant system as a function of evaporator temperature in K for a given refrigerant condensing temperature in (K).
2. Repeat step 1 for other refrigerant condensing temperature.
3. Correlate corresponding polynomial coefficients, which are obtained in previous steps versus refrigerant condensing temperature (T), a = f (T_{cd}), b = f (T_{cd}), c = f (T_{cd}), d = f (T_{cd}) [see equations (8) - (11)].
4. So, equations (6) and (7) represent the proposed governing equation in which four coefficients are used to correlate the compressor powers and condenser duties per refrigeration duty in three-stage propane refrigerant system as a function of evaporator temperature in (K) and refrigerant condensing temperature in (K).

Compressor Power and Condeser Duty in propane refrigeration System

Snaga kompresora i opterećenje kondenzatora u sustavu hlađenja propanom

August, 2011

Fig. 2. Developed computer Program
Sl. 2. Razvijeni računalni program

where the relevant coefficients have been reported in Table 1.

$$P_c = a + b\tau + c\tau^2 + d\tau^3 \tag{6}$$

$$Q = a + b\tau + c\tau^2 + d\tau^3 \tag{7}$$

where:

$$a = A_1 + B_1T_{cd} + C_1T_{cd}^2 + D_1T_{cd}^3 \tag{8}$$

$$b = A_2 + B_2T_{cd} + C_2T_{cd}^2 + D_2T_{cd}^3 \tag{9}$$

$$c = A_3 + B_3T_{cd} + C_3T_{cd}^2 + D_3T_{cd}^3 \tag{10}$$

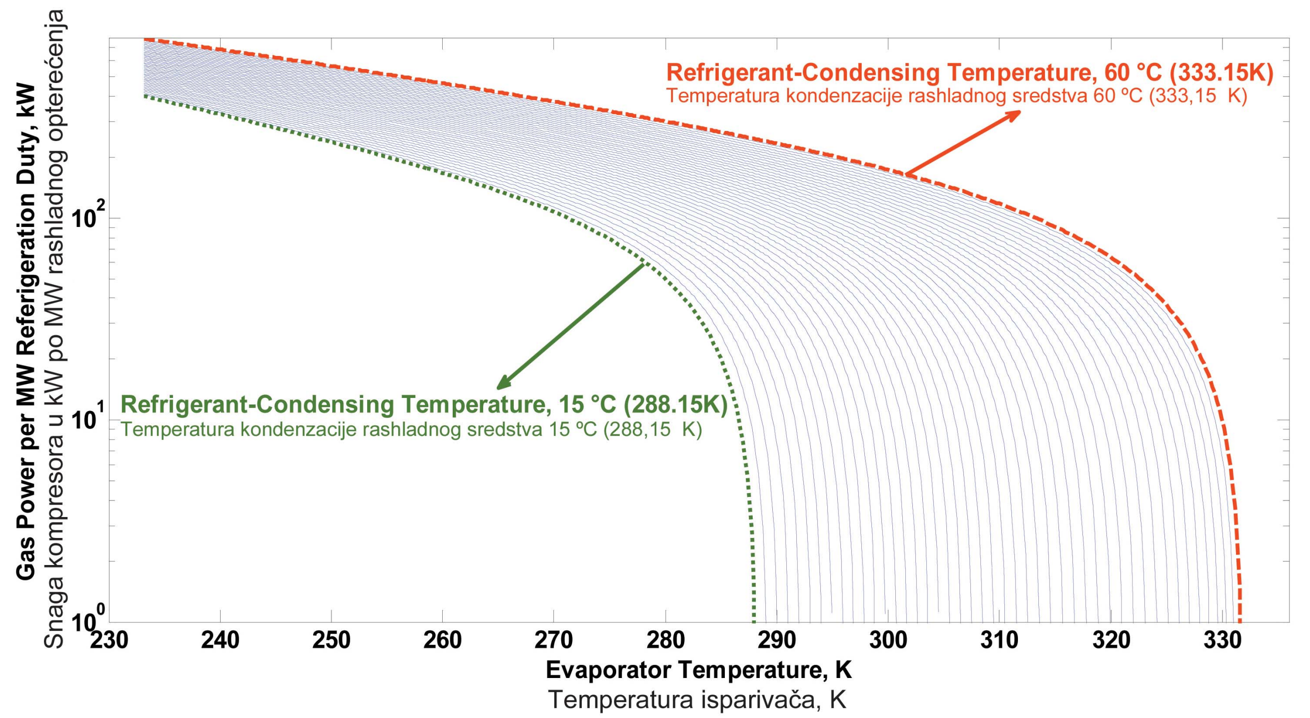

Fig. 3 Developed predictive tool performance to estimate compressor power in kW per MW refrigeration duty
Sl. 3. Dijagrami razvijeni prediktivnim programom za određivanje snage kompresora u kW po MW rashladnog opterećenja

$$d = A_4 + B_4 T_{cd} + C_4 T_{cd}^2 + D_4 T_{cd}^3 \tag{11}$$

These optimum tuned coefficients (*A*, *B*, *C* and *D*) help to cover the compressor powers and condenser duties per refrigeration duty in three-stage propane refrigerant system as a function of evaporator temperature in (K) and refrigerant condensing temperature in (K) data reported in the literature.[8]

3. Results

Figure 2 shows the developed computer program or this work. Figures 3 shows the proposed predictive tool's performance for the estimation of compressor powers per refrigeration duty in three-stage propane refrigerant system respectively as a function of evaporator temperature and refrigerant condensing temperature. Table 2 shows that the proposed predictive tool has a very good agreement with the reported data[8] where the average absolute deviation percent is 1.38%. To date, there is no simple-to-use predictive tool for an accurate estimation of the compressor powers and condenser duties per refrigeration duty in three-stage propane refrigerant system. In view of this necessity, our efforts have been directed at formulating a simple-to-use method that can help engineers and researchers. It is expected that our efforts in this investigation will pave the way for arriving at an accurate prediction of compressor powers and condenser duties per refrigeration duty in three-stage propane refrigerant system at various conditions which can be used by engineers and scientists for monitoring the key parameters periodically. The predictive tool proposed in the present work is simple and unique expression which is non-existent in the literature. Typical example is given below to illustrate the simplicity associated with the use of proposed predictive tool for rapid estimating of compressor powers and condenser duties per refrigeration duty in three-stage propane refrigerant system (Figure 1).

3.1. Example:

Estimate the power and condenser duty requirements for a three stage propane refrigeration system that will provide 26.4 × 10^6 kJh^{-1} (7.325 MW) of process chilling at a refrigerant level of -29 °C and a condenser temperature of 38 °C.

3.2 Calculation and Analysis.

The unit brake power, kW for this example from equations (6 and 8-11):

a = 1.690 943 464×10^4 (from equation 8)

b = -1.596 817 619×10^2 (from equation 9)

c = 5.212 083 406×10^{-1} (from equation 10)

d = -5.871 494 52×10^{-4} (from equation 11)

BP = 4.468 230 25×10^2 (from equation 6)

Brake power is 447 kW per MW of refrigeration duty at an evaporator temperature of -29 °C and a condenser temperature of 38 °C.

The condenser duty factor for this example from equations (7-11):

a = 1.479 411 438 8×10^4 (from equation 8)

Table 2. Accuracy of developed predictive tool for calculating compressor power in kW per refrigeration duty in MW for three-stage

Refrigerant Condensing Temperature, K	Evaporator Temperature, K	Reported data for compressor power in kW per refrigeration duty in MW for three-stage propane refrigerant systems (GPSA 2004)	Calculated values for compressor power in kW per refrigeration duty in MW for three-stage propane refrigerant systems	Absolute deviation percent
288.15	233.15	400	400.04	0.10
288.15	273.15	90	89.20	0.88
288.15	283.15	30	31.31	4.36
293.15	238.15	380	379.61	0.10
293.15	263.15	177	176.89	0.06
293.15	288.15	30	31.31	4.37
298.15	243.15	368	364.12	1.05
298.15	263.15	208	205.99	0.96
298.15	288.15	59	59.70	1.19
303.15	248.15	355	351.98	0.85
303.15	268.15	205	202.14	1.39
303.15	288.15	85	85.95	1.12
308.15	243.15	440	434.98	1.14
308.15	263.15	268	264.36	1.35
308.15	298.15	52	55.52	6.76
313.15	233.15	585	586.58	0.27
313.15	263.15	300	294.64	1.79
313.15	303.15	52	53.57	3.02
318.15	233.15	628	628.24	0.04
318.15	253.15	412	411.31	0.16
318.15	303.15	78	78.52	0.66
323.15	243.15	550	552.11	0.38
323.15	263.15	360	359.96	0.11
323.15	283.15	218	216.73	0.58
328.15	313.15	72	75.91	5.43
328.15	318.15	50	50.31	0.62
328.15	323.15	25	24.75	1.00
333.15	313.15	100	100.89	0.89
333.15	318.15	75	74.34	0.88
333.15	323.15	50	47.92	4.16
Average absolute deviation percent (AADP)				1.38%

$b = -1.266\ 830\ 674\ 1 \times 10^{2}$ (from equation 9)

$c = 4.0559\ 141\ 317 \times 10^{-1}$ (from equation 10)

$d = -4.530\ 344\ 358 \times 10^{-4}$ (from equation 11)

$Q = 1.448\ 154\ 078 \times 10^{3}$ (from equation 7)

And, from, the condenser duty factor equals 1 448 kW per MW of refrigeration duty for the same evaporator and condenser temperatures. Hence, the total power and condenser duty are:

$BP = (447)\ (7.325) = 3\ 274$ kW

$Q_{cd} = (7.325)\ (1448) = 10\ 606$ kW

4. Conclusions:

In the present work, simple-to-use predictive tool, which is easier than existing approaches, less complicated with fewer computations and minimize the complex and time-consuming calculation steps, is formulated to arrive at an appropriate compressor power and condenser duty per refrigeration duty in three-stage propane refrigerant systems as a function of evaporator temperature and refrigerant condensing temperature which are important parameters that should be considered while designing any refrigeration system. Unlike complex mathematical approaches for estimating the compressor power and condenser duty per refrigeration duty in three-stage propane refrigerant systems as a function of evaporator temperature and refrigerant condensing temperature the proposed predictive tool is simple-to-use and would be of immense help for process and gas engineers especially those dealing with gas processing. Additionally, the level of mathematical formulations associated with the estimation of compressor power and condenser duty per refrigeration duty can be easily handled by a process engineer without any in-depth mathematical abilities. Example shown for the benefit of engineers clearly demonstrates the usefulness of the proposed tools. Furthermore, the estimations are quite accurate as evidenced from the comparisons with literature data (with average absolute deviations being around 1.38%) and would help in attempting design and operations modifications with less time. The proposed method is superior owing to its accuracy and clear numerical background, wherein the relevant coefficients can be retuned quickly for various cases.

Nomenclatures:

A	Tuned coefficient
B	Tuned coefficient
B_p	Compressor brake power, kW
C	Tuned coefficient
D	Tuned coefficient
i	Matrix index
j	Matrix index
m	Matrix column number
n	Matrix row number
P	compressor power per refrigeration duty, $kW(MW)^{-1}$
Q	condenser duty per refrigeration duty, $kW(MW)^{-1}$
T_{cd}	Refrigerant-condensing temperature, K
u	coefficient of polynomial
V	Vandermonde matrix
x	polynomial independent variable

Greek letters:

α	Matrix element
ψ	Polynomia
τ	Evaporator temperature, K

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