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Shortcut Model for Predicting Refrigeration Cycle Performance

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Compression refrigeration systems are very widely used to provide cooling to sub-ambient processes. The power demand of the cycle depends strongly on the temperature at which cooling is required, the temperature at which the refrigerant is condensed, as well as the type of refrigerant being used. At lower temperatures (typically lower than −40 °C), complex refrigeration schemes, such as cascaded refrigeration cycles, may be needed, increasing the complexity of the models used to predict the power requirements for a given cooling demand. This work proposes a simple model for predicting the power consumption of such complex cycles, based on regression of more rigorous process simulation models.
A simple linear refrigeration model which relates the actual power demand of a refrigeration cycle to the ideal performance (i.e. the Carnot cycle) is developed. The model predicts the power demand prior to design of the refrigeration scheme given the condensing and evaporation temperatures of the refrigerant. The model predictions are shown to be in good agreement with those of more accurate simulation models. Case studies demonstrate the validity of the refrigeration model. The predicted power demand is shown to be within 10 % of that of Branan (2005). The simplicity of the model enables its use for optimizing the design conditions of a complex refrigeration cycle and/or the associated processing conditions.

1. Introduction

A refrigeration system is needed to provide cooling to a process stream at temperatures below ambient. Heat is removed from a process stream at a low temperature (heat source) and rejected to a heat sink, a process sink stream or a utility such as cooling water. To transfer heat from a low-temperature heat source to a high-temperature heat sink, compression work is needed. Figure 1 shows a simple vapour-compression cycle and a cascaded refrigeration cycle. Cascade cycles are usually applied in two cases (Tahouni et al., 2013): 1) when the temperature range between condensation and evaporation cannot be covered by any single refrigerant and 2) when use of a single refrigerant cycle consumes more work than a cascade cycle.

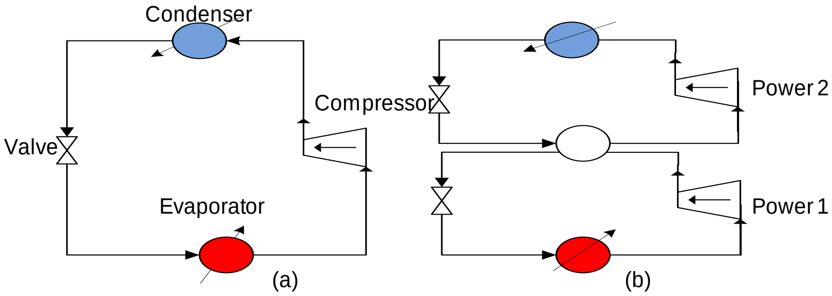

Figure 1: (a) Simple refrigeration cycle, (b) Cascaded refrigeration cycle

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Branan (2005) presented graphs that help prediction of power requirements for simple and multi-level refrigeration cycles at various temperature ranges using propane, propylene, ethane or ethylene as the refrigerant. Since it is more convenient to use correlations for evaluation of refrigeration requirements during separation process design and optimization, there have been several attempts to establish an analytical expression for predicting the actual coefficient of performance, COP_{act}, which is the ratio of the refrigeration cooling duty to the work input into the system (Eq(1)). Shelton and Grossmann (1985) developed a model to predict the coefficient of performance of simple refrigeration cycles that is a function of system temperatures and thermal properties of a refrigerant (i.e. specific heat capacity and molar latent heat of vaporization). The model can be used in preliminary design calculations and in optimization where evaluation of a large number of cycles may be required.

Bahadori and Mokhatab (2007) proposed a polynomial correlation to estimate compressor power demand and condenser duty per unit of refrigeration duty for three-level refrigeration cycles using propane as the working fluid. The theoretical basis of the correlation, a function of only evaporating and condensing temperatures is not reported. The correlation can be applied only for multi-level cycles within a narrow range of evaporating temperatures, −40 to −60 °C. Moreover, an option to reject heat to lower temperature heat sinks, rather than to cooling water or air, is not considered.

Yang et al., (2014) proposed to use the reverse Carnot model, as shown in Eq(2), to calculate the actual performance and the power requirement of a refrigeration cycle in heat exchanger network design with heat pumps. The Carnot efficiency is assumed to be 0.6. while this value can give good predictions of the shaft work for refrigeration systems providing cooling at temperatures down to approximately −40 °C, for lower operating temperatures the Carnot efficiency may be as low as 0.4 (Broughton, 1994).

$$COP_{act} = \frac{Q_{evap}}{W} = \eta * COP_{ideal} \tag{1}$$

$$COP_{ideal} = \frac{T_{evap}}{T_{cond} - T_{evap}} \tag{2}$$

Where Q_{evap} is the cooling duty, W is the actual shaft work, T_{evap} and T_{cond} are the absolute temperatures of evaporation and condensing of the refrigerant. In this work, to estimate the actual shaft work of practical refrigeration cycles, rather than assuming a constant Carnot efficiency, η, a new correlation is proposed to predict the COP_{act} as function of the ideal performance (i.e. the Carnot cycle).

2. Methodology

The first step in building the new refrigeration model is to generate performance data using a rigorous simulation package, Aspen HYSYS, where it is assumed that the detailed thermodynamic and unit operation models provide a relatively realistic representation of the refrigeration cycle. Inputs to the simulation software include the refrigerant evaporating temperature, process cooling duty and refrigerant condensing temperature. Rigorous simulations of refrigeration cycles are carried out with the following assumptions:

1. Soave-Redlich-Kwong equation of state is used to calculate thermodynamic and physical properties.
2. A centrifugal compressor that has an adiabatic efficiency of 75 % compresses the refrigerant.
3. Let-down valves are adiabatic.
4. There is negligible pressure drop in heat exchangers and pipe work and no heat gains or losses.
5. The refrigerant leaves the condenser as a saturated liquid and leaves the evaporator as a saturated vapour.
6. In a cascaded system, the temperature difference between the condensing temperature of the lower cycle and the evaporating temperature in the upper cycle is 5 °C.
7. The temperature difference between the process source stream temperature and the evaporating temperature is 5 °C.
8. The condensing temperature is variable; to account for heat rejection to ambient media or other heat sinks.

The simulation outputs include the compressor power demand and the refrigerant condenser duty. The simulation is repeated for an appropriate range of operating conditions (evaporation and condensing temperatures). The inputs and outputs are then used to correlate the actual COP with the ideal COP.

For example, Figure 2 shows a linear relationship between COP_{ideal} and COP_{act} for a cascaded refrigeration system, where ethylene and propylene are used in the lower and upper cycles. The partition temperature between the two cycles is optimised to minimise the total shaft work of the cascaded system. The comparison between the simulated results and the computed values of COP_{act} yields a coefficient of determination, R^2 of 99.5 % for the cascaded system. Figure 3 illustrates the linear relationships between COP_{ideal} and COP_{act} for simple cycles. The linear models of Figures 2 and 3 can be applied (within the appropriate range of evaporating and condensing temperatures) to predict compression power requirements more accurately than when assuming a Carnot efficiency of 0.6.

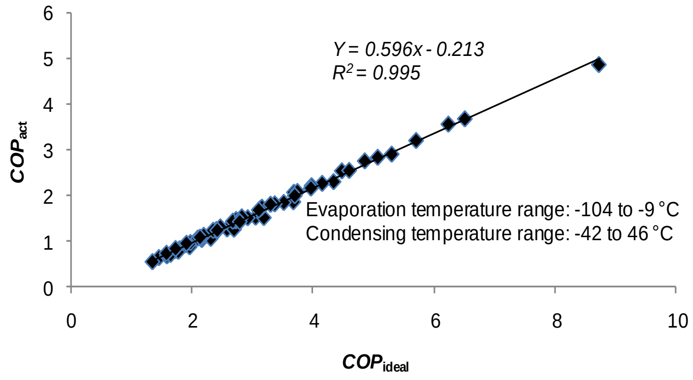

Figure 2: Linear model for cascaded cycles using ethylene/propylene as refrigerants.

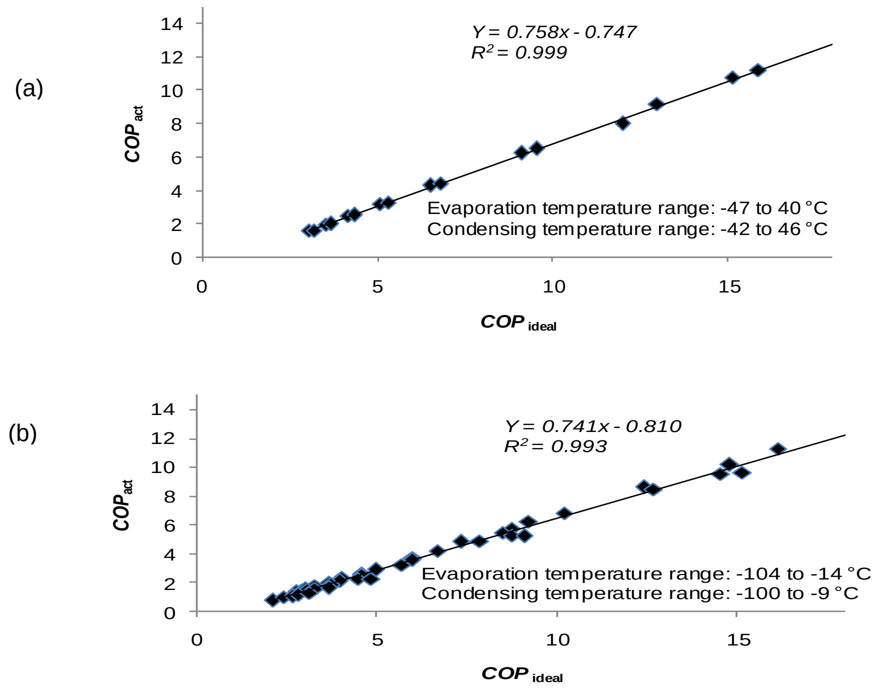

Figure 3: Linear model for a simple cycle using (a) propylene as refrigerant, (b) ethylene as refrigerant.

The relative error of the models, i.e. the difference between the rigorously calculated COP_{act} (HYSYS) and the predicted COP_{act} (model), divided by the rigorous COP_{act} (HYSYS), is less than or equal to 5 % for 85 % of the sample in the three models shown. Further statistical tests confirm the adequacy of the linear models. For example, Figure 4 presents a parity plot and a residual plot for the cascaded cycles; the model matches the simulation results nearly perfectly. It may be seen in Figure 4 (for the cascaded cycles) that there is no systematic variation between predictions of the new model and rigorous simulation results. The same approach has been applied to other refrigerants and similar results were obtained, in terms of accuracy. The potential benefit of the linear model is that it is fast and easy to implement in a synthesis framework for evaluating refrigeration power demand, as will be illustrated in the next section.

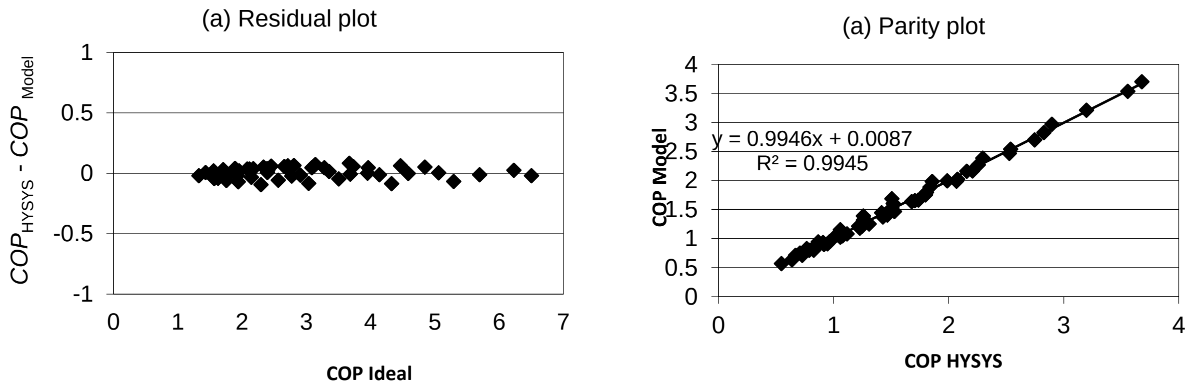

Figure 4: (a) Residual plot; (b) Parity plot of the model in Figure 2 (ethylene/propylene cascaded system).

3. Model validation and implementation

Case 1: Prediction power requirement in simple refrigeration cycle

In this case, the models are validated against the published data of Branan (2005). A simple propylene refrigeration cycle is investigated for refrigeration evaporating temperature of –35 °C, condensing temperature of 30 °C and refrigeration duty of 523 kW.

The coefficient of performance predicted using the published data of Branan is 1.8 (W = 291 kW) while the COP_{act} obtained using the equation presented in Figure 3 (b) is 2 (W = 261 kW). It can be seen that the COP_{act} predicted by the regressed correlation is within 10 % of that of Branan (2005). These results indicate that the shortcut model can be used for preliminary estimation of refrigeration cycle performance.

Case 2: Prediction power requirement in cascaded refrigeration cycle

This case compares the total shaft work prediction by the shortcut model with the shaft work calculated using HYSYS and with the published data of Branan (2005) when there is a large temperature difference between refrigerant condensing and evaporation. In this case, 523 kW cooling is required at a temperature of –82 °C. The condensing temperature is assumed to be 40 °C. In the cascaded refrigeration cycle, as shown in Figure 1(b), ethylene and propylene are used to provide cooling at –82 °C. Ethylene is the refrigerant in the lower cycle and propylene is used in the upper cycle. The partition temperature between the two cycles is optimised to minimise power demand, using rigorous simulation and found to be –40 °C, corresponding to a total shaft power demand of 781 kW. The results in Table 1 show good agreement between the model predictions and HYSYS results. To calculate the power demand from the refrigeration charts presented in Branan (2005), the cascaded cycle is decomposed to two simple cycles; the condensing temperature of the lower cycle and the cooling duty of the upper cycle from HYSYS simulations are used for refrigeration power evaluation.

Table 1 demonstrates that the shortcut model is able to predict the total power demand with reasonable accuracy in the absence of a detailed refrigeration system design.

Table 1: Comparison of total shaft work calculated by rigorous model HYSYS, published data of Branan (2005) and new model

	Power demand, kW	% Error#
Shortcut model	726	7
Published data of Branan (2005)	196 + 623 = 819	–5
HYSYS (reference case)	200 + 581 = 781	

Relative to HYSYS simulation results

Case 3: Prediction power requirement in multi-stage refrigeration cycle - two heat sources and a single heat sink

This case illustrates how the new models can be used to estimate the power demand in a multi-level cycle, with propylene as the refrigerant. The power demand in the two-level cycle is estimated by representing the two-level refrigeration cycle as a two parallel simple cycles, as shown in Figure 4(b) (Wang, 2005). Case study data are given in Table 2. In this case, model results are compared in Table 3 with HYSYS simulation results, demonstrating the usefulness of the model for estimating the net power demand in complex refrigeration cycles.

Table 2: Problem data − two heat sources and one heat sink (Wang, 2005)

	Temperature (°C)	Duty (kW)
Heat source 1	−40	3,000
Heat source2	−12.75	3,000
Heat sink	30	−
Overall temperature difference	3 °C	

Table 3: Predicted power demand for complex cycle using HYSYS and new model

Modelling approach	Power demand (kW)	% Error#
Complex cycle (HYSYS)	981+2,203 = 3,184	−
Two simple cycles (shortcut model)	1,937 + 922 = 2,859	10
Two simple cycles (HYSYS)	1,943 + 977 = 2,920	8

Relative to complex cycle simulation in HYSYS

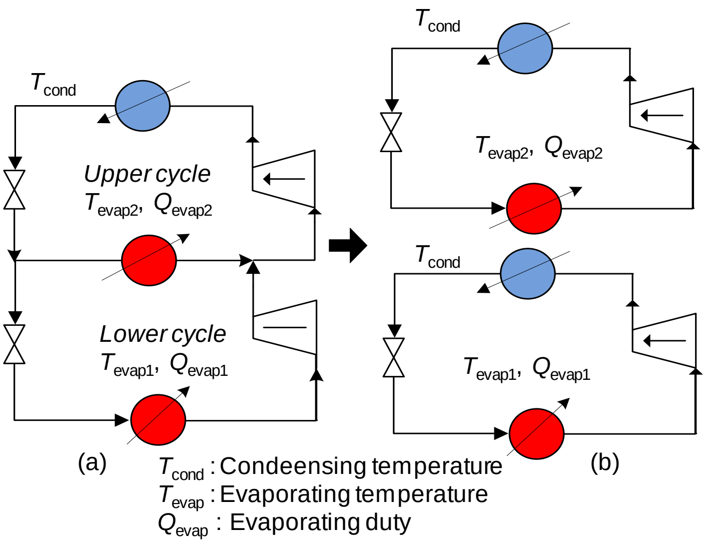

Figure 4: (a) Two-level refrigeration cycle; (b) Decomposition into simple cycles (adapted from Wang, 2005).

The error between the model and HYSYS predictions for overall shaft power prediction is about 10 %. As can be seen from the HYSYS simulation results for the two parallel cycles, this error arises mainly from the mixing effect at the inlet to the compressor in the two-level cycle. Nevertheless, this scale of error should be acceptable for preliminary estimation of refrigeration power consumption.

4. Conclusions

In this work, a linear refrigeration model, regressed from rigorous simulation results, is proposed. This model can predict the shaft work of simple, cascaded and multi-level vapour compression refrigeration systems without the need for details of the refrigeration system design. The model requires only condensing and evaporating temperatures. To demonstrate the accuracy of the presented correlation, the predictions of the shortcut model, rigorous simulation models and the published data of Branan (2005) are compared − results of the shortcut model are within 10 % of rigorous simulation results. This model has been implemented in the synthesis of a hybrid distillation-membrane separation process and its associated refrigeration system (Etoumi et al., 2014). In future works, the published data of Branan (2005) will be regressed and compared with the new refrigeration model to show the adequacy of the proposed correlation over a wide temperature range between which the specific source and sink operate.

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