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Condensation of saturated vapours on compression and estimation of minimum suction superheating

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HIGHLIGHTS

► A simple criterion is given to determine if a compressed saturated vapour condenses.
► Equations are given to estimate the degree of superheating to avoid liquid formation.
► The compressor's isentropic efficiency is taken into account.
► Examples are provided, and comparison is made with rigorous simulation.

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ABSTRACT

A very simple criterion is derived to determine whether pure saturated vapours will be superheated or partially condensed when compressed, taking the isentropic efficiency of the compressor into account. The only fluid information that is required is the compressor suction (saturation) temperature, and the ideal gas heat capacity and enthalpy of vaporisation (latent heat) at that inlet temperature. In cases where partial condensation occurs, this approach allows for the estimation of minimum degrees of superheat required prior to compression to ensure that no liquid formation takes place. The approach relies on conditions where ideal gas behaviour can be assumed; as a rule of thumb, the method should not be applied at $T/T_c > 0.6$.

1. Introduction

When a saturated vapour is compressed isentropically, it may become superheated, or it may partially condense; which of these two outcomes will occur depends on the properties of the fluid being compressed and—to a lesser degree—on the compressor efficiency [1–8]. It is imperative to avoid any condensation, as liquid formation in the compressor can rapidly damage the equipment by erosion [3,8].

One major use of compressors is in heat pumps, which have a wide range of industrial uses, typically in energy-saving configurations, and in refrigeration cycles. In refrigeration cycles, or in other heat-pumping techniques with closed loops, the working fluid is independent from the main process itself, and there is a wide range of fluids that can be chosen to best suit the process requirements in terms of physical properties and economic considerations [1,7,9].

However, in heat pump applications such as vapour recompression distillation [4,10–12], or in heat-integrated distillation columns [13,14], the fluid to be compressed cannot be independently chosen; moreover, the compressed fluid is a saturated vapour in these applications, and it is invaluable to know whether condensation will occur, and if so, how much superheating of the compressor suction vapour is required to avoid this.

To answer the first question, Patwardhan [3] developed a criterion to determine whether isentropic compression will lead to superheating or partial condensation. This criterion requires the saturated inlet compressor temperature, the fluid's liquid heat capacity, and its latent heat as a function of temperature. Patwardhan [3] also proposed replacing the latter with a correlation requiring the acentric factor and the critical temperature. With the assumption of liquid incompressibility, the criterion is as follows:

$$\frac{C_p^L}{R} < \beta \text{ (superheated)} \quad \frac{C_p^L}{R} > \beta \text{ (partially condensed)} \tag{1}$$

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where

$$\beta = -\frac{T_0}{R}\frac{d}{dT}\left(\frac{\lambda(T)}{T}\right)_{T=T_0} \tag{2}$$

Eq. (1) requires the liquid heat capacity, C_p^L, while Eq. (2) requires the saturated compressor suction temperature, T_0, and the temperature-dependent latent heat, λ.

Patwardhan [3] suggested the use of a correlation in Reid et al. [15] to obtain β as a function of acentric factor, ω, and critical temperature, T_c:

$$\beta = 7.08\left(1-\frac{T}{T_c}\right)^{-0.646}\left(-0.646+\frac{T_c}{T}\right) + 10.95\omega\left(1-\frac{T}{T_c}\right)^{-0.544}\left(-0.544+\frac{T_c}{T}\right) \tag{3}$$

This work proposes an alternative to Patwardhan's [3] method; it uses only the ideal gas heat capacity and latent heat, both evaluated at T_0. Therefore, neither the temperature dependence of λ, nor ω, nor T_c is required. It also allows for the inclusion of the effects of the compressor's isentropic efficiency. Lastly, equations are derived for the estimation of suction superheat required to ensure no condensation in the compressor.

2. Theory and derivation

2.1. Isentropic and non-isentropic compression

An ideal gas, when compressed isentropically from pressure P_0 to P_1, experiences an increase in temperature from T_0 to some temperature $T_{1,\mathrm{isentropic}}$; the relationship between these temperatures and pressures can easily be deduced, assuming constant C_p^{IG}:

$$\frac{P_1}{P_0} = \left(\frac{T_{1,\mathrm{isentropic}}}{T_0}\right)^{\frac{C_p^{IG}}{R}} \tag{4}$$

If the compressor is not perfectly isentropic, its efficiency, η, can be taken into account, again assuming constant C_p^{IG}:

$$\eta \equiv \frac{W_{s,\mathrm{isentropic}}}{W_{s,\mathrm{actual}}} = \frac{H_{1,\mathrm{isentropic}}-H_0}{H_{1,\mathrm{actual}}-H_0} = \frac{T_{1,\mathrm{isentropic}}-T_0}{T_1-T_0} \tag{5}$$

$$T_{1,\mathrm{isentropic}} = \eta(T_1-T_0)+T_0 \tag{6}$$

where T_1 is the actual exit temperature from the compressor. Substituting Eq. (6) into Eq. (4):

$$\frac{P_1}{P_0} = \left(\eta\left(\frac{T_1}{T_0}-1\right)+1\right)^{\frac{C_p^{IG}}{R}} \tag{7}$$

The vapour pressure curve describes the pressures and temperatures at which a substance is saturated; if, at a given pressure, the fluid's temperature exceeds the saturation temperature, the fluid is superheated. The Clausius–Clapeyron equation is useful for relating a known point on the saturation curve to one at a similar temperature assuming constant λ:

$$\ln\left(\frac{P_1}{P_0}\right) = -\frac{\lambda}{R}\left(\frac{1}{T_1}-\frac{1}{T_0}\right) \tag{8}$$

If a new variable is defined as $\tau = 1/T_1$, and the logarithm of Eq. (7) is taken, the following is obtained:

$$\ln\left(\frac{P_1}{P_0}\right) = -\frac{C_p^{IG}}{R}\ln\left(\frac{\tau T_0}{\eta-\tau T_0(\eta-1)}\right) \tag{9}$$

and using τ in Eq. (8) gives:

$$\ln\left(\frac{P_1}{P_0}\right) = -\frac{\lambda}{R}\left(\tau-\frac{1}{T_0}\right) \tag{10}$$

First, the assumption is made that the saturated vapour becomes superheated on compression. If, for a given compressor pressure ratio (P_1/P_0), τ in Eq. (9) is lower than the τ in Eq. (10), the assumption was correct, and the compressed vapour will indeed be superheated. Otherwise, if the opposite is found to be true, then the compressed fluid must be condensed. This is represented graphically in Fig. 1, for benzene (partially condensed) and propylene (superheated), with plots of Eqs. (9) and (10). Note that in the case of condensation, the actual compression profile runs along the saturation line; the representation of isentropic compression in Fig. 1 assumes that only vapour exists. If it enters the liquid region, it means that the assumption is incorrect. Furthermore, propylene was included in this plot, and treated as an ideal gas for illustrative purposes; in reality, it does not approximate an ideal gas at these conditions.

Since both equations pass through T_0 and P_0, it is sufficient to compare their gradients at that point to determine whether condensation will occur. Eq. (10) is a straight line, and its gradient is already known to be $-\lambda/R$. For Eq. (9), the gradient can be found by taking the derivative of $\ln(P_1/P_0)$ with respect to τ to obtain $-C_p^{IG}T_0\eta/R$. Therefore, the proposed criterion is, very simply:

$$C_p^{IG}T_0\eta < \lambda \ (\text{superheated}) \quad C_p^{IG}T_0\eta > \lambda \ (\text{partially condensed}) \tag{11}$$

Because only the gradient at T_0 is considered, and C_p^{IG} and λ are evaluated at that temperature, it can be shown that the only assumptions in Eq. (11) are that the gas is ideal and that the specific volume of the saturated liquid is negligible in comparison with the specific volume of the saturated vapour. Both of these are reasonable assumptions far from the critical point.

Durandet [9] implicitly presented a similar criterion to Eq. (11), but the derivation is based solely on the fluid properties and can therefore not take into account the compressor's efficiency.

2.2. Superheating before compression

If it is found that the saturated vapour condenses on compression, the issue can be circumvented by superheating the inlet to

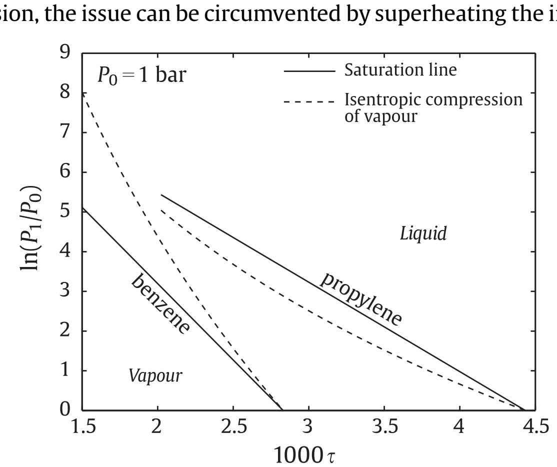

Fig. 1. Plot of $\ln(P_1/P_0)$ as a function of τ for propylene (superheated on isentropic compression) and benzene (condensed on isentropic compression).