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The Composition of Gases Vented from a Condenser

R. N. Lyon

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THE COMPOSITION OF GASES VENTED FROM A CONDENSER

R. N. LYON

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
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NOMENCLATURE

h_{fg}	the molal heat of vaporization of the process fluid
$\overline{h_{fg}}$	the mean value of h_{fg} in the temperature range between T_o and T_c
n	the number of moles of a constituent of the vented mixture
n_n	the number of moles of noncondensable gases
n_p	the number of moles of process vapor
P	absolute pressure
P_c	the pressure in the condenser
P_n	the partial pressure of the noncondensable gases in the vented mixture
P_p	the partial pressure of the process vapor in the vented mixture
R	the gas constant
T	absolute temperature
T_c	the saturation temperature of the process fluid at P_c
T_o	the temperature at which the vented mixture leaves the condenser
v	molal volume
v_{fg}	the molal volume of vaporization of the process fluid
v_n	the molal volume of the noncondensable gases
v_p	the molal volume of the process fluid
V	a volume of the vented mixture, nv
z	compressibility, Pv/RT
z_{fg}	the compressibility of vaporization of the process fluid, $P_p\ v_{fg}/RT$
$\overline{z_{fg}}$	the mean value of z_{fg} in the temperature range between T_o and T_c
z_n	the compressibility of the noncondensable gases, $P_n\ v_n/R\ T_o$
z_p	the compressibility of the process vapor, $P_p\ v_p/R\ T_o$

THE COMPOSITION OF GASES VENTED FROM A CONDENSER

R. N. Lyon*

ABSRACT

Designers of systems that involve condensers often need to predict the amount of process vapor that accompanies the noncondensable gases that are vented from the condensers.

The following approximation appears to provide, in many cases, reasonably accurate values for the mole ratio of process vapor to noncondensable gases in the vented mixture:

$$\frac{n_p}{n_n} \approx \frac{R\ T_c\ T_o}{\overline{h_{fg}}\ (T_c - T_o)} - \frac{1}{2}. \qquad (1)$$

The approximation is particularly applicable to flash and direct-contact power systems for geothermal brines and ocean thermal energy conversion (OTEC).

More rigorous relationships are available for exceptional cases.

INTRODUCTION

Well designed condensers flow the process vapor from the condenser inlet across the condensing region to a vent region where noncondensable gases can be removed continuously, or accumulated for periodic removal. When the process fluid is used in a closed Rankine cycle entirely above atmospheric pressure, the principal source of noncondensable gas will be that dissolved in make-up fluid, and venting is usually not a serious problem. At the opposite extreme is a subatmospheric condenser for vapor being condensed by direct contact with a stream of water, or other cool fluid, that is saturated with gas at atmospheric pressure and where

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*Consultant, Energy Division.

the vapor originates either from or in direct contact with warm fluid that is also saturated with noncondensable gases.

The latter situation occurs, for example, in flash and direct-contact systems for geothermal power plants and for ocean thermal energy conversion (OTEC).

The gaseous mixture that is withdrawn from condensers will be saturated with the process-fluid vapor at the temperature of withdrawal, and this can pose several problems:

1. If the vapor is flammable, it must be recovered or flared to avoid the danger of fire or explosion.

2. The process fluid may be sufficiently valuable to require recovery from vented mixture.

3. If the condenser operates below atmospheric pressure, a vent compressor will be required. The power required by the first stage or two of a mechanical compressor will usually be dominated by the power required for adiabatic compression of the process vapor in the mixture that is being compressed in that stage, and the bulk of the heat removed in the first few interstage coolers will be the latent heat of the condensing process vapor. Water-jet and barometric-leg compressors tend, in principle, to approach isothermal compression, but the size of the compressor is determined by the volume flow rate of the incoming mixture from the condenser.

For these and perhaps other reasons, designers need to estimate the amount of process vapor in the effluent mixture as a function of P_c, the condenser pressure, and T_o, the temperature at which the mixture leaves the condenser.

ANALYSIS

In those cases where the constituents of the vented mixture all behave as ideal gases, we find, as described below, that

$$\frac{n_p}{n_n} \approx \frac{R\,T_c\,T_o}{\overline{h_{fg}}\,(T_c - T_o)} - \frac{1}{2}\,, \qquad (1)$$

where n_p/n_n is the mole ratio of process vapor to noncondensable gas in the mixture, R is the gas constant, T_c is the saturation temperature of the pure process vapor at P_c, the pressure of the condenser, and $\overline{h_{fg}}$ is a mean value of the molal heat of vaporization of the process fluid in the temperature range between T_o and T_c.

Development of Approximation (1) discloses the assumptions that it includes, and indicates more rigorous equations or approximations for nonideal gases and vapors.

We start by defining the "compressibility" of any gas or vapor as

$$z \equiv \frac{P\,v}{R\,T}\,, \tag{2}$$

where, of course, P and T are the absolute pressure and absolute temperature of the gas, and v is its molal volume. The compressibility will be unity for an ideal gas, and its value for saturated vapors does not change as rapidly with temperature as does the specific volume.

We next make the assumption that each constitutent gas fills the volume, V = n v, that is occupied by the mixture and that it has no interaction with any of the other constitutent gases, except that the sum of the individual partial pressures of the constituent gases is P_c, the total pressure in the condenser.

We also assume that the noncondensable gases are insufficiently soluble in the liquid process fluid to effect a serious change in the saturation temperature of the liquid. These are both reasonable assumptions, for example, if oxygen and nitrogen are the noncondensable gases, and if water, Freon, or a light hydrocarbon is the process fluid.

It follows from those assumptions that

$$\frac{n_p}{n_n} = \frac{z_n\,P_p}{z_p\,P_n} = \frac{z_n\,P_p}{z_p\,(P_c - P_p)}\,, \tag{3}$$

where, again, the subscripts p and n refer to the process fluid and noncondensable gases.

We now draw on the Clapeyron equation:

$$\left(\frac{\partial P}{\partial T}\right)_{\text{saturation}} = \frac{h_{fg}}{T\, v_{fg}} , \qquad (4)$$

where v_{fg} is the increase in molal volume of the process fluid when it vaporizes.

If we define a compressibility of vaporization as

$$z_{fg} \equiv \frac{P\, v_{fg}}{RT} , \qquad (5)$$

we obtain a modified Clausius-Clapeyron equation:

$$P_p = P_c \exp\left[\frac{\overline{h_{fg}}\,(T_o - T_c)}{\overline{z_{fg}}\, R\, T_o\, T_c}\right] \qquad (6)$$

and

$$\frac{n_p}{n_n} = \frac{z_n}{z_p}\, \frac{1}{\exp\left[\frac{\overline{h_{fg}}\,(T_c - T_o)}{\overline{z_{fg}}\, R\, T_c\, T_o}\right] - 1} \qquad (7)$$

Next, we note that

$$\frac{1}{e^x - 1} \approx \frac{1}{x} - \frac{1}{2} , \qquad (8)$$

within about 10% or less, when $x < 0.9$:

x	0	0.1	0.3	0.5	0.7	0.8	0.9	1.0
$1/(e^x - 1)$	∞	9.51	2.86	1.54	0.99	0.82	0.69	0.58
$1/x - 1/2$	∞	9.50	2.83	1.50	0.93	0.75	0.61	0.50
% error	—	-0.09	-0.9	-3	-6	-8	-11	-14

Thus, we find that

$$\frac{n_p}{n_n} \approx \frac{z_n}{z_p}\left[\frac{\overline{z_{fg}}\, R\, T_c\, T_o}{\overline{h_{fg}}\, (T_c - T_o)} - \frac{1}{2}\right] \tag{9}$$

and when the compressibilities all approach unity,

$$\frac{n_p}{n_n} \approx \frac{R\, T_c\, T_o}{\overline{h_{fg}}\, (T_c - T_o)} - \frac{1}{2} \, . \tag{1}$$

DISCUSSION AND CONCLUSIONS

At 300°K (80°F), $h_{fg}/RT = 18$ for water and $= 8$ for isobutane. Thus, with water as the process fluid, we need to keep $(T_c - T_o)/T$ to less than about 0.05 if we use Approximation (1).

In the case of isobutane, the error can be held to 10% or less if $(T_c - T_o)/T$ is 0.1 or less; but we need to check to see whether we should use Approximation (9), since for isobutane at that temperature, $z_p = 0.90$ and $z_{fg} = 0.88$. At 278 K (40°F), z_p for isobutane is 0.94 and z_{fg} is 0.93.

In OTEC systems the value of $(T_c - T_o)/T$ will usually be less than 0.02. This means that if water is the process fluid, and if the noncondensables are nitrogen, oxygen, and any other gases that behave like ideal gases, the mole ratio of the vented mixture will be greater than 2.3 moles of water to one mole of noncondensable gas. If, as is more likely, $(T_c - T_o)/T$ is 0.01, then the effluent mixture will contain 5.1 moles of water vapor per mole of noncondensable:

Temperature	$\frac{h_{fg}}{RT}$	z_p	z_{fg}	Moles, Process Fluid/Mole, Noncondensables			
				$(T_c - T_o)/T = 0.02$		$(T_c - T_o)/T = 0.01$	
				Appr. (9)	Appr. (1)	Appr. (9)	Appr. (1)
Water							
300 K (80°F)	18	1	1	2.3	2.3	5.1	5.1
278 K (40°F)	19	1	1	2.1	2.1	4.8	4.8
Isobutane							
300 K (80°F)	8	0.90	0.88	5.6	5.8	11.7	12.0
278 K (40°F)	9	0.94	0.93	5.0	5.1	10.5	10.6

In the above calculations, we have not differentiated between T_c, T_o, and an intermediate temperature at which we calculate $\overline{h_{fg}}$ and $\overline{z_{fg}}$. It appears from the results, however, that only a few percent error is involved in that lack of rigor.

The compressibilities of saturated vapors are always unity or less. Thus, the vaporization compressibility and the simple compressibility of the process vapor will always tend to cancel each other in Eq. (7) and Approximation (9). That fact is illustrated by the close agreement between the results for isobutane using Approximations (9) and (1).

On the other hand, as seen in Eq. (7) and Approximation (9), the mole ratio in the vented mixture will be exactly proportional to the compressibility of the noncondensable gases.

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