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CONTAMINANTS IN CIRCULATING REFRIGERANT

ZANIECZYSZCZENIA W CZYNNIKU ZIĘBNICZYM

Abstract

Contaminants are inevitable in the refrigeration cycle. Lubricant, water and moist air are the main contaminants in circulated refrigerant. This paper attempts to show how the presence of such contaminants influences the thermodynamic parameters of the refrigerating cycle and the mixture, which comes at the beginning.

Keywords: refrigerant, contaminants, mixture, specific enthalpy, thermodynamic cycle, refrigerating cycle, positive-displacement compressor

Streszczenie

Zanieczyszczenia w czynniku ziębniczym obiegu ziębniczego są nieuniknione. Obecność substancji smarnej, wody, powietrza wilgotnego to główne zanieczyszczenia czynnika obiegowego obiegu ziębniczego. W artykule przedstawiono wpływ obecności wymienionych zanieczyszczeń na podstawowe parametry obiegu ziębniczego, a w szczególności na entalpię właściwą powstałej mieszaniny.

Słowa kluczowe: czynnik chłodniczy, czynnik ziębniczy, zanieczyszczenia obiegu ziębniczego, mieszanina, entalpia właściwa, obieg termodynamiczny, obieg chłodniczy, obieg ziębniczy, sprężarka wyporowa

1. Introduction

Along with refrigerant, contaminants¹ can also circulate in the refrigeration cycle with a lubricated reciprocating compressor. These contaminants are very problematic. They can include inert gases (such as air), moisture (in vapour, aerosol and drop) and lubricant (in bulk liquid, aerosol and vapour [7]). Therefore, there is refrigerant, lubricant and moist air in the mixture in the refrigerating cycle (refrigerating- air-vapour-oil mixture).

The refrigeration cycle needs an almost sterile environment to survive.

Contaminants in the refrigerant have an influence on thermodynamic parameters, heat exchange and compressor work as well as the throttle valve (change in flow, pressure drop, change of refrigerants parameters, such as specific enthalpy, viscosity, surface tension, etc.). Therefore, the presence of contaminants in refrigerant should be considered in thermodynamic calculations.

Additionally, the refrigerant in the refrigeration cycle is considered as an ideal one, but indeed, it should be treated as a real gas.

2. Air in refrigerant – non-condensable contaminant (NCG)

Air is one of the most difficult contaminants in refrigerant. This contaminant can cause excessive head pressure and increased operating temperature [2, 9]. The result is higher utility costs, degradation of lubricant effectiveness, and premature compressor problems [6, 8, 13].

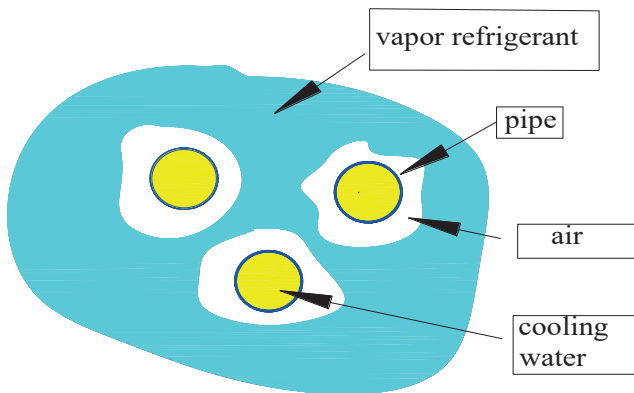


Fig. 1. Configuration of layer around coil pipe

Many studies talk about, for example in [10], the author presenting the temperature profile of R404A in a coil pipe for three air volume contents of 0%, 1,5% and 3%.

¹ Ingredient which is not refrigerant in refrigerating cycle, is contaminant.

According to the author, up to 5 % volume fraction of air overall heat-transfer coefficient increases up to 50 % in the water-cooled refrigerating unit.

Refrigerant only condenses during condensation, whereas air remains gaseous, aggravating near the heat exchange surface in the condenser [3] (even smattering of air around or inside the pipe causes a decrease of the heat exchange coefficient, causing an increase of pressure in the heat exchanger above the saturation pressure [2]).

3. Moisture in refrigerant

Another contaminant in the refrigeration system is moisture. Refrigeration systems are very sensitive to moisture in the refrigerant side of the system. If moisture gets into the system, failure may occur due to ice formation in expansion valves, capillary tubes or evaporators, corrosion of metals, copper plating, chemical damage to insulation in hermetic compressors or other system materials.

Sources of moisture in the refrigeration system include:

- ▶ Faulty equipment drying in factories and service operations,
- ▶ Introduction of moisture during installation or service operations in the field,
- ▶ Low-side leaks (resulting in entrance of moisture-laden air),
- ▶ Leakage of water-cooled condenser,
- ▶ Oxidation of certain hydrocarbons of oil to produce moisture,
- ▶ Wet oil, refrigerant or both,
- ▶ Decomposing cellulose insulation in hermetically sealed units.

Water freely absorbs into refrigerant as if being soaked up by a dry sponge. Due to its solubility characteristics, water will continue to absorb into refrigerant until saturation is achieved. Once saturation is exceeded, a flooded condition is created and the actual amount of water in the system cannot be determined by refrigerant analysis.

Refrigerant moisture directly causes the formation of acids resulting in metal corrosion copper plating and chemical damage to the insulation in hermetic compressors and other system materials. Metal corrosion may lead to rust and pitting of motor bearings and copper plating may form on bearings causing a reduction in tolerance. Moisture contamination occurs when moisture enters the refrigeration system. Moisture can exist in three forms: water, solid and gas. Therefore, if contaminants are introduced into the system, they act to reduce compressor efficiency, effectiveness and durability. If moisture enters in to a refrigeration system, it combines with the refrigerant to form an acidic solution, which may erode internal compressor components. Moisture does not actually cause direct compressor failure; the failure results from the failure of a part, which has been weakened as a result of the effects of rust and corrosion [4]. Any amount of water above 50 ppm is potentially dangerous and should be removed [8].



4. Lubricant in refrigerant

A lubricant is necessary in almost all the vapour compression systems, particularly for the right operation of the positive displacement compressor. The cylinder – piston assembly, the reciprocating movement and friction of piston give the main characteristic of a positive displacement compressor. The main role of lubricant is to ensure the existence of a thin lubricant film allowing the lubrication of the mechanical moving elements (pistons, connecting rod/crank, valves, ...) in order to protect them against wear. Lubricant is used in order to reduce the friction.

It assures a correct compressor operation and cylinder – piston unit performance. The sliding mechanism with a cylinder and a piston compressor is shown in Fig. 2.

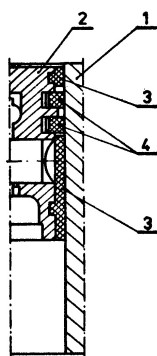


Fig. 2. Sliding mechanism of cylinder and piston in compressor 1 – cylinder, 2 – piston, 3 – oil ring rails, 4 – piston packing rings

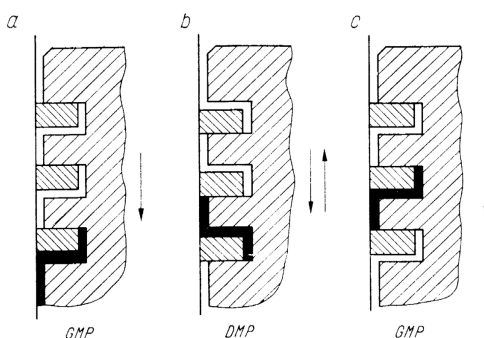


Fig. 3. Scheme blow up of operation of piston ring

The mechanism of movement of lubricant is shown in Fig. 3.

Because of a shortage of data about the amount of oil circulating in the cycle, it is exemplified contained in ISO deal with the amount of oil in the compressor. Inside the lubricated compressor, the refrigerant, unavoidably, picks up some mineral oil or synthetic lubricant. In addition, the refrigerant from the non-lubricated (dry) compressor may contain oil.

Lubricant, according to ISO 8573 (which pertain to compressed air and air in refrigeration cycle also exists) in compressed air can belong to one of the three following categories:

- a) bulk liquid,
- b) aerosol,
- c) vapour [7].

The amount of oil (concentration) in air is presented in ISO 8573 [7].

Lubricant circulates in whole refrigeration cycle, which is presented in Fig. 4.

Table 1. Maximum oil content [7]

Class	Maximum concentration [mg/m ³]
1	0,01
2	0,1
3	1
4	5
5	25

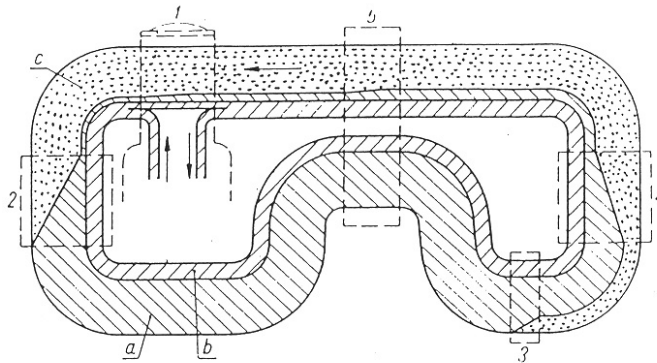


Fig. 4. Scheme of cycle of refrigerant and oil in refrigerant cycle (origin unknown)
a-liquid oil, b-vapor oil, c – refrigerant, 1 – compressor, 2 – condenser, 3 – throttling valve,
4 – evaporator, 5 – heat exchanger

ASHRAE research demonstrates a content of oil in refrigerant sampled from 10 randomly selected chillers. All samples contained excess oil (from 1% to 8 %). It caused a decline of energy efficiency depending on the increase of oil in cycle (from 2 % to 15 %).

Table 2. Efficiency lost according to percent oil content in evaporator [9]

Percent oil in evaporator	Efficiency loss
1–2 %	2 – 4 %
3 – 4 %	5.5 – 8 %
5 – 6 %	9.5 – 11 %
7 – 8 %	13.5 – 15 %

Although oil, moisture and air are existent in refrigeration systems, they do not provide for in the thermodynamic calculation. In this article, the first part of the thermodynamic calculation for a mixture consists of oil, moisture and air (oil and moist air). It could help to describe the mixture consisting of refrigerant with oil, moisture and air.

5. Other refrigerants in refrigerant – impurities (remains)

Remains of refrigerants sometimes can exist in working refrigerant. Chemical analysis of the refrigerant is required to determine that appropriate product specifications are met. The identification of contaminants, required chemical analysis (gas chromatography [1]), and acceptable contaminant level, will be published in ARI Standard 700 [1]. Maximum allowable levels of contaminants are shown in Tables 3.

Table 3. Characteristic of zeotropic blends and their maximum allowable levels of contaminants [1]

	Reporting Units	Reference Section	R-408A	R-409A	R-409B	R-410A	R-410B	R-411A	R-411B
CHARACTERISTICS¹:									
Refrigerant Components	N/A	N/A	R-125/ 143a/22	R-22/ 124/142b	R- 22/124/142b	R-32/125	R-32/125	R-1270/ 22/152a	R-1270/ 22/152a
Nominal Comp	% by weight	N/A	7/46/47	60/25/15	65/25/10	50/50	45/55	1.5/87.5/11.0	3/94/3
Allowable Comp	% by weight	N/A	5-9/45-47/ 45-49	58-62/23- 27/14-16	63-67/23-27/ 9-11	48.5-50.5/ 49.5-51.5	44-46/54-56	0.5-1.5/87.5- 89.5/10-11	2-3/94-96/ 2-3
Bubble Point ¹	°C @ 101.3 kPa °F @ 14.70 psia	N/A	-44.6 -48.2	-34.7 -30.4	-35.6 -32.1	-51.4 -60.6	-51.3 -60.4	-39.5 -39.1	-41.6 -42.8
Dew Point ¹	°C @ 101.3 kPa °F @ 14.70 psia	N/A	-44.1 -47.4	-26.4 -15.5	-27.9 -18.2	-51.4 -60.5	-51.6 -60.2	-36.6 -33.9	-40.0 -40.0
Critical Temperature ¹	°C °F	N/A	83.10 181.6	106.9 224.4	106.9 224.4	71.40 160.5	70.80 159.4	99.10 210.4	96.00 204.8
VAPOR PHASE CONTAMINANTS:									
Air and Other Non Condensables	% by volume @ 23.9°C	5.10	1.5	1.5	1.5	1.5	1.5	1.5	1.5
LIQUID PHASE CONTAMINANTS:									
Water	ppm by weight	5.4	10	10	10	10	10	10	10
All Other Volatile Impurities	% by weight	5.11	0.5	0.5	0.5	0.5	0.5	0.5	0.5
High Boiling Residue	% by volume	5.8	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Particulates/Solids	Visually clean to pass	5.9	pass	pass	pass	pass	pass	pass	pass
Acidity	ppm by weight (as HCl)	5.7	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Chloride ²	No visible turbidity	5.6	pass	pass	pass	pass	pass	pass	pass
¹ Bubble points, dew points and critical temperatures, although not required, are provided for informational purposes. ² Recognized chloride level for pass/fail is about 3 ppm. N/A Not Applicable -- Data Not Available Refrigerant data compiled from Refprop 7.0.									

Volatile Impurities including other refrigerants

Although oil, moisture and air are existent in refrigeration systems, it does not provide for in the thermodynamic calculation. In this calculation, the first part of the thermodynamic calculation for a mixture consists of oil, moisture and air (oil and moist air). It could help to describe the mixture consists of refrigerant with oil, moisture and air [13].

6. The mathematics modelling of a mixture of moist air and lubricant in the vertical cylinder

In thermodynamics, humid air is considered a mixture of ideal gases. However, such an approach is not entirely appropriate, when taking into account an influence of higher pressures and temperatures in the compressor. The lubricating substances could be divided into natural (mineral oil), synthetic oil and half-synthetic oil.

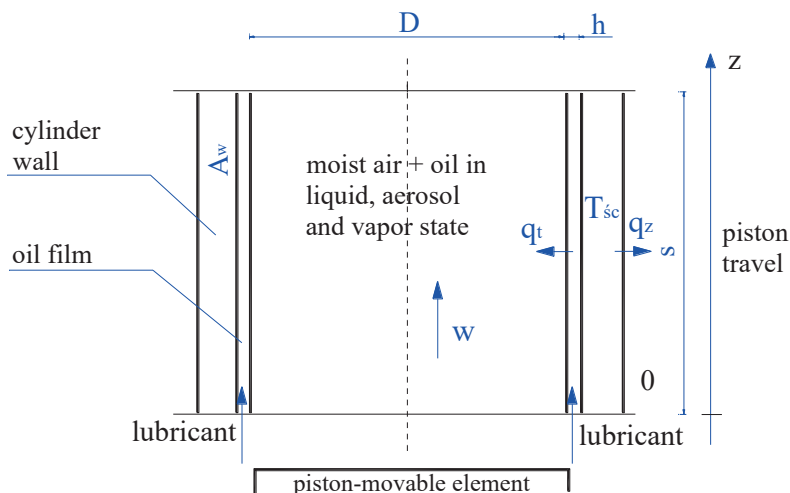


Fig. 5. Piston-cylinder arrangement with mixture inside cylinder

During lubrication of the cylinder's smooth surface, an oil-film is emerging on the cylinder's wall (further on, a partial dispersion of lubricating substance takes place in the working space of the compressor that results in appearance of aerosol). As a consequence of the piston's forward-backward movement and its friction against the cylinder's wall, the wall's temperature rises. If the temperature is high enough, the wall "dries out". The oil takes over the heat from the cylinder's wall (cooling function) and turns into vapour. In the compressors' cylinder, a structure of flux of the air and lubricating substance mixture in the form of liquid, steam and aerosol is emerging. The heat that is transferred during the exchange between the air and external environment is described as the external heat of transformation \dot{q}_z (Fig. 5, 6). The value of this heat and its sign directly influence the pace of thermodynamic transformation taking place in the compressor. It is assumed in the paper that the process of compression is accompanied of exchange of the heat with the environment. Thus, in order to solve equation systems constituting a mathematical model of the compression process, what is needed is knowledge of the density of the stream of heat relating to the length of piston stroke.

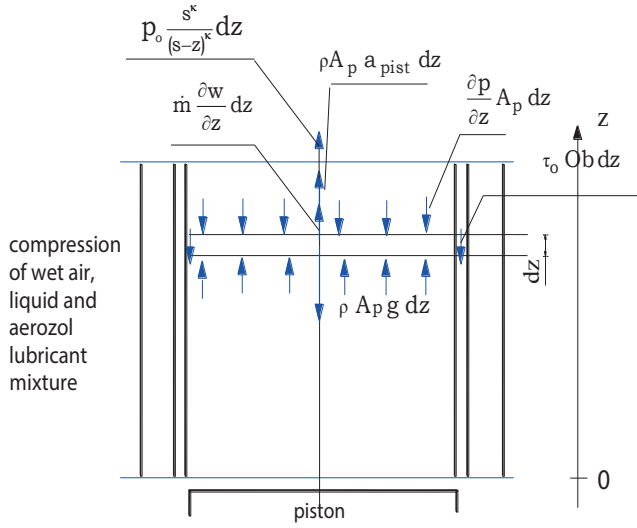


Fig. 6. Forces operative on elementary layer of fluid

Mass conservation law, momentum conservation, energy conservation law

In the analysed case of the compression air-lubricant mixture, we are dealing with the “haze” system. The phenomenological method has been adopted here to describe the model. This method assumes that it is justified to treat two-phase liquid as the two penetrating and interacting continuous units.

The two-phase as well as one-phase flux is governed by the mass, momentum conservation and energy conservation laws supplemented by constitutive equations (i.e. equations of state, strain, momentum transport and energy transport as well as chemical features of the liquid). The governing equations of the flow (continuity, momentum and energy) can be displayed either in the form of integral or in differential.

The mass conservation law adapted to the flowing mixture is given by equation:

$$A_p \left(\frac{\partial \rho}{\partial \tau} \right) + \frac{\partial \dot{m}}{\partial z} = 0$$

Consider the force balance an elementary layer of mixture in the flow field is given by equation:

$$\frac{\partial \dot{m}}{\partial \tau} - A_p \frac{dp}{dz} = \tau_o * Ob + A_p \rho \frac{wdw}{dz} - A_p \rho g + A_p a_{pist} + p_o \frac{s^\kappa}{(s-z)^\kappa}$$

The energy conservation law (I principal of thermodynamics):

$$\rho A_p \frac{\partial h}{\partial \tau} + \frac{d \left[\dot{m} \left(h + \frac{w^2}{2} \right) \right]}{dz} = \pi D_{in} \dot{q}_z - A_p \rho g w$$

Nomenclature

a_{pist}	– acceleration of piston [m/s ²],
A_p	– cross sectional area of cylinder [m ²],
D_{in}	– inside diameter of cylinder [m],
ρ	– gravitational acceleration [m/s ²],
h	– specific enthalpy [J/kg],
\dot{m}	– mass flux [kg/s],
Ob	– cross-sectional circumference of cylinder [m],
p, p_d, p_k, p_r	– pressure, inlet pressure, outlet pressure, reduced pressure [Pa],
\dot{q}_z	– rate of heat flow [W/m ²],
s	– piston stroke [m],
T, t	– temperature [K], [°C],
ν	– molar volume of the mixture [m ³ /kg],
w	– velocity [m/s],
κ	– polytropic exponent [–],
τ	– time [s].

A method of the solution of an example

The presented mathematics model of the compression process takes the form of differential equations, depicting a change of the selected parameters along the cylinder's length in the form, which is directly useful for computer programs:

The initial values used for the mathematic model solution is: 1. initial air pressure equal to atmospheric pressure, 2. initial specific enthalpy value of the air in the compressors' entrance.

The presented system of differential equations can be solved by numeric integration methods. The Runge-Kutty fifth range method has been adopted in order to solve the above-mentioned differential equations [12].

7. Conclusions

initial calculations show differences in specific enthalpy between the specific enthalpy of dry air, wet air and a mixture of wet air and lubricant in liquid and aerosol state in the elevated pressure and temperature (Table 4).



Table 4. Specific enthalpy of mixture

T	Specific enthalpy of wet air ^{*)}	Specific enthalpy of lubricant ^{*)}	Specific enthalpy of mixture ^{*)}
[K]	[kJ/kg]	[kJ/kg]	[kJ/kg]
298	809,26	46,16	809,73
308	822,42	65,54	823,083
318	835,55	85,45	836,40
328	848,64	105,92	849,70
338	861,76	126,94	863,03
353	881,49	159,54	883,08

^{*)} Example results of testing, when the pressure of compressed air is 0,2 MPa

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