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ABSTRACT

Coolers and cleaners which affect the compressor's efficiency and application region are important equipments in compressed gas/air system. There are many scientific workers who work at the investigation of cooler and cleaner of compressor. Prof.V.Chlumsky introduced a new type of cooler named surface froth gas cooler in PROCEEDINGS of the 1972 PURDUE COMPRESSOR TECHNOLOGY CONFERENCE. But he did not offer the information of the design. On the base of experimantal research by the authors this paper offers the method of designing the surface froth gas cooler which has double function of gas cooling, clening and other advantages: high heat transfer coefficient, more safety and less system vibrition. The paper also offers a new heat transfer formula worked out by authors and introduces a method of measuring the oil microconstituents in the gas.

Key words: compressor, cooler, heat exchanger, gas cleaning.

I. INTRODUCTION

The temperature and pressure of gas increase after being compressed. There are intercoolers and aftercoolers in a multistage compressor for saving power or/and decreasing the temperature of discharging gas. Generally there are much impurities in the compressed gas/air, which affect the performance of compressors and is easy to form oil carbon deposits that is a fire source in the compressed air system. In order to increase the heat transfer efficiency and remove the impurties in the gas, the authors have designed a new type of gas cooler which has the function of both cooling and cleaning gas. This gas cooler is to combine shell-tube heat exchanger with a froth-producing chamber and a separator to become a new one. In order to gain the method of designing this type of heat exchanger, the authors made various experiments and worked out the calculating formulas. The gas cooler that was designed with this method has been used in the industries, the characteristics of cooling is much better than the traditional one. Prof. v. Chlumsky once introduced this type of cooler, but he did not offer the design method and information. On the base of authors' experiments this paper presents the design method and compares the designed values with measured ones. This paper also introduces a method of measuring the oil content in the compressed air. The informations will be a helpful reference to engineers working in the field of heat transfer and compressor.

II. COOLER CONSTRUCTION AND ITS HEAT TRANSFER PROCESS

The principle and construction of the cooler are shown in Fig.1. It consists of four parts: froth-producing chamber at the bottom, heat exchanger in the middle, gas separator and filter. The hot compressed air enters through the branch 1, ascendes through the holes of the perforated plate 2 and together with circulating water (or other suitable liquid) brought to plate through opening 3 forms froth on the upper side of the plate 2, carried to tube bundle 4. On the plate 2, the temperature of hot air decreases rapidly since circulating water evapoats and absorbs heat. There is very intensive heat transfer in the turbulent froth, from the froth to the wall of the tube bundle and from the tubes to the cooling water entering the shell 11 of the cooler through inlet 10. The cooling water being directed by several baffles 12 across the tube bundle leaves the cooler through the outlet 13.The froth, after passing the tubes of the bundle, flows into the separater 7, where the circulating water is separated from the air taking away simultanously all of the oil and any impurities carried from the compressor. The cooled saturated air comes out from the air cooler through the outlet 9. The separated water after settling in the bank 6 is automatically recycled through tube 5 to the perforated plate 2.

The heat exchange between hot and cold fluids takes place at first in the froth-producing chamber. The Figure 2 shows the heat transfer process (Curve 1--3). In the process part of circulating water evaporats to vapour and absorbs large quantity of heat from the hot air, resulting rapid temperature decrease of their. The temperature of the unvaporized water increases and that of hot air decreases untill both temperature become equivalent. This is the process 1--3. In Figure 2 the curves 1--2 and 1'--2' are heat transfer processes due to water evaporating, the curves 2--3 and 2'--3' are due to water temperature increasing. The process 1--3 is a complex heat and mass transfer process, but we can calculate simpely. Though large quatity of heat is absorbed by evaporating water, the quantity of water is a little so the increase of the enthalpy is a little. The process 1--2 can be considered a isenthalpy. Under this assumed condition for a simple calculate, the temperature of point 2 can be found on the enthalpy-humility diagram (i--D disgram), as shown in Fig.3. It is noted that the i--D diagram is plotted in accordance with the gas pressure of cooler. The enthalpy I1 is the value of the compressed air just entering the cooler.

$$I1 = 1.005\ t_1 + D_1(2501 + 1.8903 t_1)$$

where t1 and D1 are parameters at the inlet of the cooler.

If more accurate calculation is needed we can assume t2 according to heat transfer equiliblrium formula and theorem of humid air:

t2 is the temperature of the end of process 1--2. The heat transfer from the hot air is:

$$Q = Q1 - Q2 = m(I1 - I2)$$

since moisture content of air is constant, so for one kilogram humid air:

$$Q = 1.005\ (t_2 - t1) + D_1(2501 + 1.8903(t_2 - t1))$$

Because t2 is a saturated temperature of gas, so the saturated pressure P2 can be obtained from the table of saturated vapour and the moisture content D2 can be ditermined by formula:

$$D_2 = 622 \frac{P2}{P - P2}$$

where P is mixture pressure of humid air.

The increasing of moisture content of humid air is because of the circulating froth water which absorbs the heat of the hot air. Therefore the absorbed heat can be ditermined by the formula:

$$Q = (D2 - D1) \times r$$

where r is the latent heat of vaporization at the temperature of circulating water.

The closer the absorbed heat by water and the released heat from air is, the more accurate the assumed temperature t2. T2 can be obtained so long as providing the accuracy E through repeatedly calculating.

$$E = \frac{Q2 - Q1}{Q2}$$

Hot air mixing with the circulating water forms supersaturated air. The water state existing in the air is fog and froth which flows together with air. The supersaturation magnitude is equal to that the rate of flow frothing water minuses the moisture content of the air. The temperature of unevaporating water rises and also absorbs a part of heat as shown in process 2'--3 in Fig.2. The temperature of point 3 can be determined according to released heat Q_{23} in process 2--3, and absorbed heat by water $Q_{2'3}$. The process 2--3 is isobar, so dq=dI,

$$Q_{23} = dIxm_g = (I_2 - I_3)x\ m_g$$

$$Q_{2'3} = (T_3 - T_{2'}) \times m_w \times C_p$$

The temperature of point 3 is assumed at first and then examined with heat equilibrium equitions. It is easy to make out by repeating several times. After entering the tube bundles the fluid of two-component and two-phase exchanges the heat with cooling water outside of the tube, which is heat transfer process 3--4. In this process vapour is condenced to water and the wet air partially becomes water. The froth and water brushes the inside surface of the tubes continuouslly, which enhances heat exchange and at the same time cleans the dirt on the wall of tubes. The temperature of points 3,4,3',4' are taken and the logarithmic mean temperature differnece is calculated, the temperature of point 4 is given by cooler's users, while the temperature of 3' will depend on designer's assume. Generally it is about 10°C higher than that of cooling water at inlet.

III. DETERMINATION OF THE HEAT TRANSFER COEFFICIENT

The method to calculate the heat transfer coefficient of this type of heat exchanger has not been found from published references. The authors sout out the datas measured in the laboritary and make out the formula of calculating the heat transfer coefficient in the tubes. The actual designed coolers verify that is reliable.

1. Heat Transfer Coefficient Hi Inside the Tubes

In order to enhance the heat exchange, usually it is desirable to increase the fluid velocity, nevertheless in this type of heat exchanger the authors consider that the fluid velocity shouldn't be too high since flow resistance increase rapidly. The froth has increased the turbulence level and enhanced the heat exchange. See referance [1], it is suitable to control the fluid velocity ranging from 4--6 m/s and heat transfer performance is excellent. The heat transfer coefficient is also interrelated with added frothing water, which increases with the increase of water capacity but the flow resistance also increases more rapidly. The experiment shows that it is suitabale to control the ratio of circulating water to flow air to about 0.5 l/m^3. At this ratio, the heat transfer coefficient Hi can be calculated by the following formula:

$$\frac{Hi \cdot di}{k} = 5.05 \times 10^{-8} \times Re^{2.29}$$

the range of Re is about $1.4x10^4$ -- $1.9x10^4$
$Pr = 0.69$ -- 0.70

where $Re = \frac{di \cdot Gq}{u}$

2. The Heat Transfer Coefficient Ho Outside the Tube

There are many referendes to introduce how to get the heat transfer coefficient Ho outside the tube. From reference [3] we can use Donohue method to determine Ho.

$$\frac{Ho \cdot do}{k} = 0.23\ Re^{0.6} \left(\frac{cp \cdot u}{k}\right)^{0.3333} \left(\frac{u}{uw}\right)^{0.14}$$

the range is: 3 Re 20000

3. Overall heat transfer coefficient U

While designing this type of cooler, the data of dirt thermal while designing this type of cooler, the data of dirt thermal resistance outside tubes is taken as the same as that introduced in reference [2]. For inside of the tube, as froth and water scours the surface of the tube the magnitude of dirt thermal resistance is less than that introduced in reference [2].

$$\frac{1}{U} = \frac{1}{Hi} + \frac{1}{Ho} + \frac{do \cdot ts}{d_m \cdot ks} + \frac{r_i \cdot do}{di} + ro$$

IV. THE COMPARISON OF THE DESIGNING VALUE WITH THAT MEASURED IN A DESIGNED COOLER

Using the method above, the authors have designed a aftercooler for an air compressor whose displacement capacity is 2400 Nm^3/hr. The measured data is listed in Table 1, showing that it is closer that measured data compares with designed data. The following reasons are why the temperature of measured data of cooled air is lower than that of designed.

1. In designing the heat transfer process is assuemed to be isothermal one, that is, the released heat from the fluid is all absorbed by cooling water. Actually there is natural convection around the cooler and the wall of chamber will transfer heat to suroundings.

2. The thermal resistance of heat exchanger is given according to experience which is less for a new cooler, so the characteristics measured in the cooler is better.

3. The formula tends safety. The designer of the cooler considers always many worst working conditions. In fact, generally they do not appear at the same time, so the actual performance of the cooler is better than the designed one.

TABLE 1. Comparison of the designed data with that measured

item	unit	data designed	data measured
Heat transfer area	m^2	7	7
overall heat transfer coefficient	$W/m^2 \cdot °C$	500	580
temp. of gas at inlet	°C	160	168
temp. of gas at outlet	°C	55	45
temp. of cooling water	°C	30	34
rate of cooling water	kg/h	9000	8000
flowing resistance	mm H20	2000	1200

V. THE MEASUREMENT OF OIL MICROCONSTITUENTS

The cooler indroduced in this paper has the functions of cooling and cleaning air. In order to know the extent of the cleaned air, the authors measured the oil microconstituent in the compressed air in accordance with National Standard of China (GB4830-84) "Pressure Range and Quality of Air Supply for the Industrial Process Measurement and Control Instruments". The compressed air out of the after cooler introduced in this paper is saturated air.

The method of measurement used in the test is ultraviolet absorption spectrum, and sampling is according to the regulation in GB4830-84. The flow diagram is shown in Fig.4 in which compressed air flows from main tube through pressure reducing valve to the sampling bottles in which CCl_4 liquid is contained. There are 3-4 bottles connected series in the sampling system and CCl_4 liquid absorbs oil vapour in the air. The air that flows out off the bottles enters the flowmeter and then is released.

The instrument used to measure the oil microcontituents is uv-240 type ultraviolet spectrophotometer which is equiped with micro-computer. In analysis process, at first, to get certain amount of compressor lubricating oil makes a standard curve that is the variation of peak value of the absorbing spectrum with different oil content in the air. In the test, the absorption wave length of lubricating oil is 265 millimicron. After sampling. It is measured that the valume of CCl_4 liquid which has absorbed the oil vapour. Then, put certain CCl_4 liquid contained oil in to uv-240 type spectrophotometer. The microcomputer can print out the value of sample containing oil content after starting instrument. Comparing this value with air flowing amount through the flow meter, it can be known that how much oil content in per cubic meter air. The analysis result in the test is 8.5 mg/m^3 (standard state).

VI. CONCLUSION

1. The construction of froth gas cooler is a new type heat exchanger, in which a new method of enhancing heat transfer is used. The cooler has the characteristics of high heat transfer efficiency, the function of cleaning gas, which is suitable to be used in the industry.

2. The informations introduced in the paper can be used for engineer satisfactory to design such type of gas cooler and the formula tends towards security.

NOMENCLATURE

A	area (m^2)
d	diameter of the tube (m)
D	moisture content of the humid air (g/kg).
Gg	gas mass flow rate per unit area (kg/h·m^2).
Ggm	water mass flow rate per unit area (kg/h·m^2).
I	enthalpy (KJ/kg)
k	thermal conductivity (W /m^2·k).
m	mass flow rate (kg/h).
P	pressure bar.
Q	heat rate w/h .
r	heat resistance (m^2·k/W).
Re	Reynolds number.
t	temperature (K).
U	overall heat transfer coefficient (W/m^2·k).
u	viscosity (kg/m-s).

SUBSCRIPTS

g	gas
v	vapour
w	water

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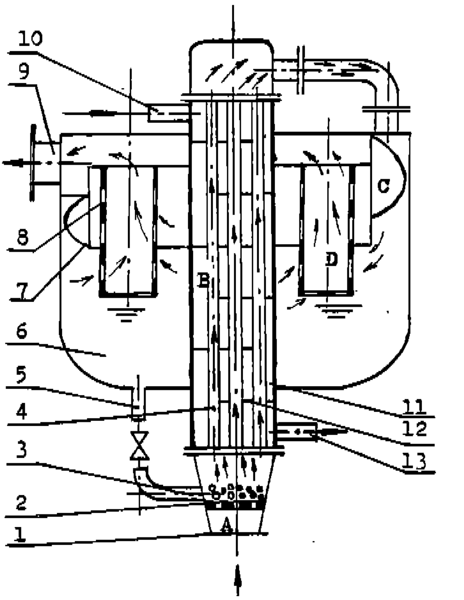

Fig. 1 construction of the cooler

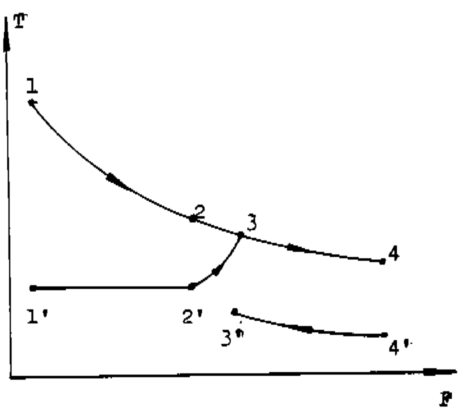

Fig.2 variation of temp. in the cooler

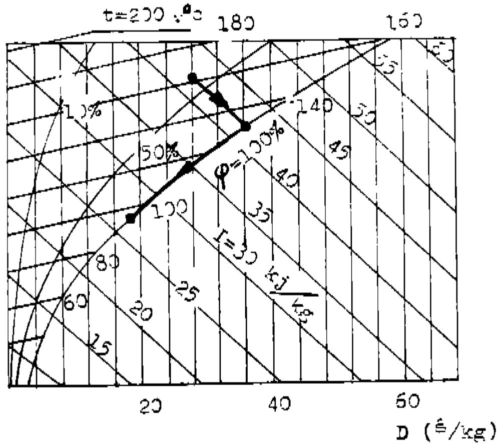

Fig.3 heat transfer process on
i--D diagram

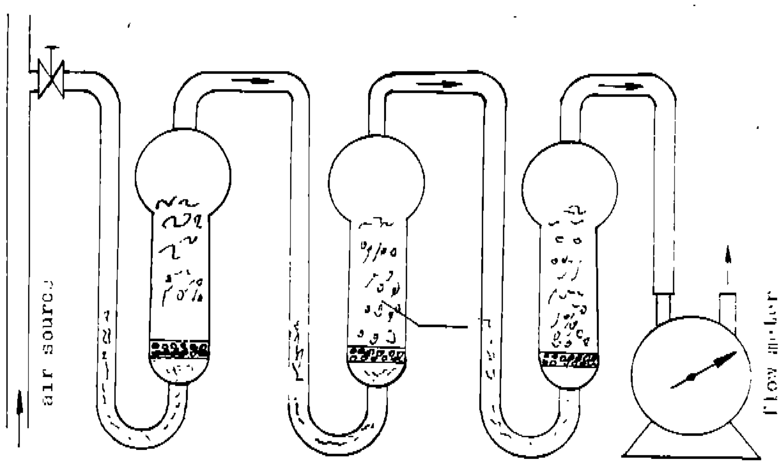

Fig.4 sampling system of compressed air