Analyses on the circulation of heat pump using the flue gas as the low temperature heat reservoir

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Abstract: According the combustion theory, fist law of thermodynamics and gas law, analyses are made on the dew-point temperature, saturated humidity and enthalpy of flue gas of combusted natural gas exhaust. The calculating equations for these parameters are derived and the corresponding calculating results are given in patterns of curves, which can be used as the base for actual engineering design. A new technical flow chart is put up what have a heat exchanger and three parallel heat pumps. Basing on it the actual COP of each heat pump can exceed 3. If the flue gas temperature is cooled down from 100℃～200℃ to 40℃～30℃, the use of the sensible heat and latent heat of partial condensation of flue gas can be at a high level, and the thermal efficiency of natural gas can be raised 10%～20%.

Keywords: flue gas, dew point, condensation, heat pump, flow chart.

LIST OF SYMBOLS

V volume of air or flue gas
α air factor
d specific humidity of flue gas
T temperature of air or flue gas (K)
t temperature of air or flue gas (℃)
M molecule weight
P pressure, partial pressure (Pa)
ϕ condensation ratio
ρ specific density
I enthalpy
φ relative humidity of air
H heat value of natural gas
r heat of vaporization of water
R gas constant
C isobar specific heat

Subscripts

a air
vp water vapor
o standard state
f flue gas
act actual specific air requirement

1. INTRODUCTION

It is known that heat pump have enormous potential for saving energy, particularly in building heating processes. They are the only heat recovery systems， which enable the low temperature heat to be raised to more useful levels for heating. It is very popular for air heat pump in the regions of the east and south of china in winter. But in north china the using of air heat pumps has been hampered by the fact their efficiency and capacity will become very low when the outdoor temperature is below -10℃. So that using waste heat is the main method to overcome the disadvantages of heat pumps.

Along with the adjustment of energy structure of china. Natural gas is used more and more, particularly in district heating, CHP and many other commercial uses. A lot of natural gas exhaust has a emission temperature of 150℃～200℃, some time even reaches 200℃～300℃. A high return water temperature level in heating system has restricted the using of sensible heat and latent heat of flue gas. For the conventional water heating system has a standard supply water temperature 95℃ and a standard return water temperature 70℃, The temperature difference between medium and flue gas is generally equal to or more than 80℃ in natural gas boilers, so that heat efficiency and economic are very low by using of sensible heat and latent heat of flue gas directly. As the flue gas of natural gas is very clean, so that the corrosion of equipment produced by flue gas is very small. A new technology flow chart is put up in this paper, which can largely raise the heat using efficiency of natural gas.

2. Humidity Of Flue Gas

The condensation of water vapor begins when the state of saturation for the steam in the flue gas is reached while cooling the flue gas. This point called the dew point, and its temperature is the dew-point temperature. At the dew point the steam pressure equals the saturation steam pressure of water, which is, as an approximation, for a total pressure about 1 bar.

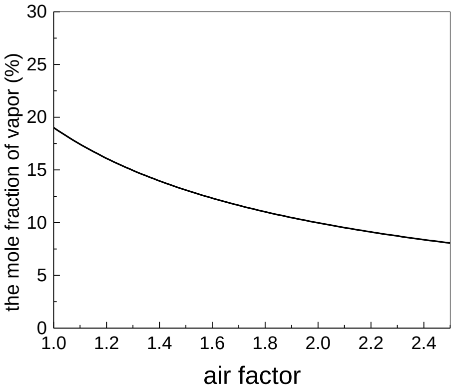
Determining relationship between the saturation humidity and temperature of flue gas is very important for using the sensible heat and latent heat of flue gas. According the thermodynamics theory the saturation temperature steam pressure of water, flue gas temperature and total pressure influence the saturation humidity. Because the main composition of natural gas is methane, so that in this paper we assumed natural gas only has one composition of methane. The combustion reaction equation can be described as follow:

$$CH_4 + 2(O_2 + 3.76N_2) = CO_2 + 2H_2O + 7.52N_2 \qquad (1)$$

According the equation (1), the stoichiometric air requirement is $V_0 = 9.52$, and stoichiometric amount of flue gas is $V_f^0 = 10.52$. In order to insure the natural gas burning completely, the actual air requirement is greater than the stoichiometric air requirement. The air factor is defined as the ratio of actual air requirement and the stoichiometric air requirement, hence:

$$\alpha = \frac{V_{act}}{V_0} \qquad (2)$$

Fig.1 and fig2 are the results from equation (1) and (2). From the figures the cures of volume and mass humidity of water vapor in flue gas as a function of the air factor are given. It is shown that the amount of humidity is decreasing with the air factor increasing. The conventional air factor for natural gas combustion changes form $\alpha = 1.1$ to $\alpha = 1.5$, the volume percent of humidity in flue gas changes form 18% to 12%, and the mass percent of humidity in flue gas changes form 12% to 8%. About 1.6kg water vapor will produce when 1Nm^3 natural gas burnt completely.



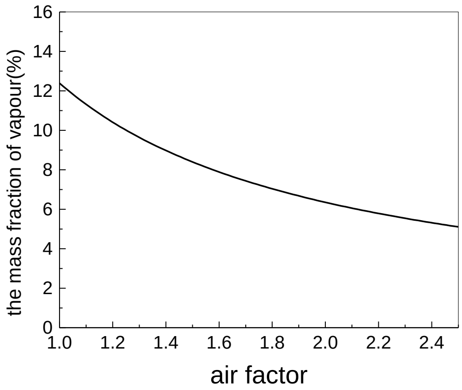


Fig.1 volume composition of humidity in flue gas as a function of the air factor

Fig.2 mass composition of humidity in flue gas as a function of the air factor

2.1 SPECIFIC HUMIDITY OF FLUE GAS

We describe the mass of a humid flue gas mixture as an alternative to speaking in terms of m_{vp} and m_f. The way is to specify the mass ratio called specific humidity or humidity ratio

$$d = \frac{m_{vp}}{m_f} \qquad \text{kg water vapor/kg dry flue gas} \tag{3}$$

Which represent the number of kilograms of water vapor that correspond to 1 kilogram of dry flue gas in the given mixture. As the pressure of flue gas is near the pressure of atmosphere, the pressure of water vapor in flue gas is very small, the specific volume is very great, so that the water vapor and flue gas can be assumed as theoretical gas. The pressure-volume-temperature equations can be described as follow:

$$p_f \cdot V = m_f \cdot R_f \cdot T \tag{4}$$

$$p_{vp} \cdot V = m_{vp} \cdot R_{vp} \cdot T \tag{5}$$

combine eq.(3) with eqs. (2) and (5):

$$d = \frac{m_{vp}}{m_f} = \frac{p_{vp} \cdot R_f}{p_f \cdot R_{vp}} \tag{6}$$

$$MR = R_0 \tag{7}$$

we combine eqs. (6) and (7) to conclude that

$$d = \frac{m_{vp}}{m_f} = \frac{M_{vp} \cdot p_{vp}}{M_f \cdot p_f} \tag{8}$$

according equations (1) and (2) the molecular weight of flue gas can be calculated by using formula $M_f = (250.56 + 276.08(\alpha - 1))/(8.52 + 9.52(\alpha - 1))$, and molecular weight of water vapor is

$M_{vp}=18$. Equation (8) combine with M_f and M_{vp} to transform as：

$$d=\frac{1800\cdot p_{vp}}{(250.56+276.08(\alpha-1))/(8.52+9.52(\alpha-1))\cdot p_f} \tag{9}$$

2.2 CONDENSATION RATIO OF WATER VAPOR IN FLUE GAS

When the state of flue gas saturated with water vapor is called dew point. The pressure is called dew-point pressure and the temperature is called dew-point temperature. If the temperature of flue gas cooled down below the dew point the condensation occurs. The condensation ratio of water vapor in flue gas is defined as the mass ratio between condensation water and total vapor produced from the combustion of specific volume of natural gas.

The ambient air state has been assumed to be in state with temperature of 0℃, pressure of 101325Pa, and relative humidity of φ. The total amount of vapor in flue gas is sum of vapor produced in combustion and vapor from air. According about analyses the condensation ratio of water vapor in flue gas can be calculated by equation:

$$\phi=\frac{V_{H_20}\rho_{H_2O}+d_0\alpha V_0\rho_a\varphi-d\left(V_{CO_2}\rho_{CO_2}+V_{N_2}\rho_{N_2}+V_0(\alpha-1)\rho_a\right)}{V_{H_20}\rho_{H_2O}}$$

$$=\frac{1607+46.53\times\alpha\varphi-d(11.377+12.309\times(\alpha-1))}{1607} \tag{10}$$

Fig. 3 is the result calculation of the condensation ratio against the dew-point temperature of flue gas with different air factor and relative humidity of ambient air by equation (10). It shows that the air factor and relative humidity of air influence the dew-point temperature and the condensation ratio of flue gas, the influence of air factor is greater than that of relative humidity of air. The dew point temperature changes in the range from 59℃ to 38℃ when the air factor varies in the range from 1 to 3. The tendency of condensation ratio increases with the flue gas temperature decreasing. If the relative humidity of air is below 100%, the condensation ratio will be less than 1 when the temperature achieved 0℃. Because partial water vapor produced in combustion process of natural gas saturates the excess unsaturated air. At the same air factor situation the dew-point temperature and condensation ratio change agree with the relative humidity of air.

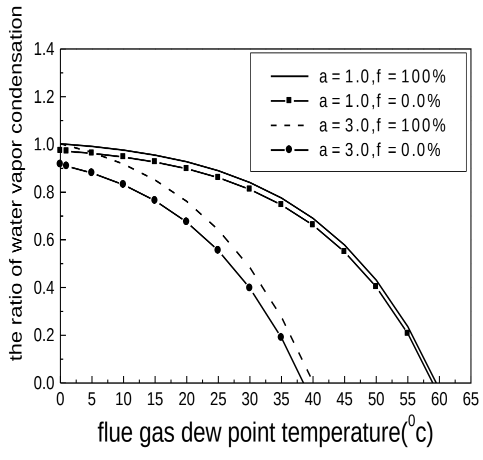


Fig.3 the curves of condensation ratio as function of flue gas temperature

3 THERMAL EFFICIENCY OF NATURAL GAS

According the first low of thermodynamics the enthalpy of the total flue gas from 1Nm^3 natural gas burnt completely can be calculated from:

$$I_f = V_{CO_2} C_{CO_2} t_f + (1 - \phi + d_0 \alpha \varphi \rho_a / \rho_{H_2O}) \; V_{H_2O} C_{H_2O} t_f$$
$$+ V_{N_2} C_{N_2} t_f + (\alpha - 1) V_0 C_a t_f + d_0 \alpha V_0 \qquad (11)$$

The thermal efficiency of natural gas can be defined as the ratio between the sum of low heat value of natural gas and the latent heat minus the enthalpy of flue gas emission to the surroundings, which can be available:

$$\eta = \frac{H_l + \phi V_{H_2O} \rho_{H_2O} r - I_f}{H_l} \qquad (12)$$

The calculation result reveals the thermal efficiency of natural gas changed with the flue gas temperature (Fig. 4)。The diagrams show that no condensation occurs when the flue gas temperature is higher than the dew point, and the heat efficiency goes up with the flue gas temperature decreasing in linear pattern. But when temperature is cooled down below the dew point condensation occurs, the heat efficiency increases sharply with the flue gas temperature decreasing in parabola pattern, and the increasing rate is greater when the temperatures are between the dew point that the condensation occurs to 20℃ than it is when between 20℃ to 0℃. Secondly the air factor influences the heat efficiency, it declines with the air factor increasing, the temperature is higher, and the efficiency is lower. Now the temperature is about 200℃ for most emission flue gas. If the outlet temperature of flue gas drops from 200℃ to 30℃, the heat efficiency will increases from 77%～92% to 103～108%(related the lower calorific value), the efficiency lift is in the range from 26% to 16%, especially for great air factor and high outlet flue gas temperature the energy saving is obvious.

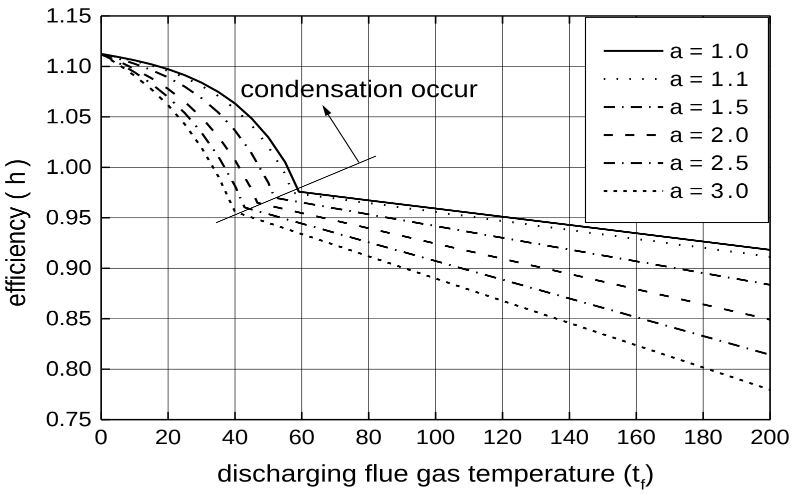


Fig. 4 natural gas heat efficiency as function of
outlet flue gas temperature and air factor

4 FLUE GAS HEAT PUMPS

Along with the developing of fan coil heating and floor radiant heating technology, the 40℃～60℃ water is widely used to heating. The efficiency to produce 40℃～60℃ water is very low by using the natural gas exhaust to heat directly. We put up a technical flow (fig. 5) to use the waste heat of outlet flue gas completely. First the higher temperature flue gas through a waster boiler heats some mount of 40℃ water to 60℃,and the flue gas temperature drop to about 80℃; Then the lower temperature flue gas through three parallel heat pumps heats 40℃ water to 60℃ for heating circulation. Its principle is illustrated in fig.5.

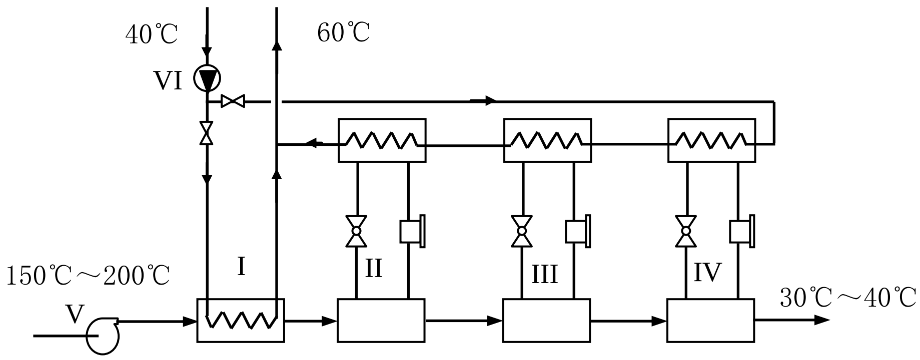


Fig.5 flue gas heat pump technical flow chat

I waster heat boiler；II、III、IV flue gas heat pump；Vfan；VI water pump

The difference between the condensing and evaporating temperature ($t_{co} - t_{ev}$) is the gross or maximum possible temperature lift. The net temperature lift between heating water and flue gas ($t_f - t_w$) is less than the gross temperature lift by the sum of the temperature difference driving forces in the evaporator and condenser. So that only when the evaporating temperature and the gross temperature lift are both very low, the using level of the flue gas waste and the actual COP of heat pump are both high. For the single stage heat pump the gross temperature lift should be 40℃～50℃，or else the COP would be very low. For the three parallel heat pumps, the gross temperature lift for each heat pump is designed to be 40℃～50℃, so the COP is high. The factors should be considered for selecting the working fluid for the heat pump: the condensing pressure should not be more than 20 bar, the evaporating pressure should be more than atmospheric pressure to prevent produce vacuum, and the specific volume delivering teat capacity should be high; the working fluid should be security and friendly to environment. So we selected R134a as working

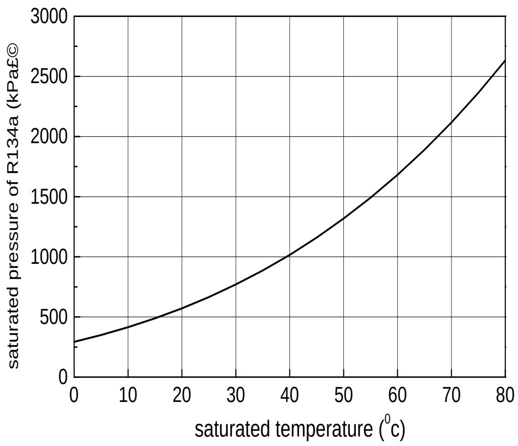


Fig. 6 variation of saturated pressure with saturated temperature for R134a

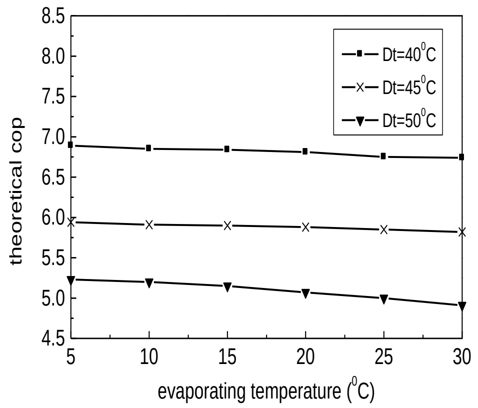


Fig.7 theoretical COP against the evaporating temperature for R134a

fluid. The CSD equation is be used to analyze the thermal thermodynamic properties for the heat pump operating. The fig.6 is a plot of saturated pressure against saturated temperature for R134a. Fig.7 is a plot of theoretical Rankine coefficient performance (COP) against the evaporating temperature for R134a according different gross temperature lifts being 40℃, 45℃ and 50℃. Fig.7 shows that the gross temperature lift influences the COP obviously, if it increases 5℃ the COP will be cut down in the range 1.6 to 1.8, and the condensing temperature has a little influence on the COP.

In practice the operation of a mechanical vapor compression heat pump consists of two heat exchangers, a compressor, an expansion valve and a working fluid. There are flow resistance and unorganized heat transfer in every components of the heat pump. So that the actual amount of teat delivered, high-grade energy input and COP are different from Rankine cycle heat pump. The gross temperature lift and condensing temperature impact the COP ratio between the practice cycle heat pump and Rankine cycle heat pump. When the gross temperature lift is in the range 40℃ to 50℃, and the condensing temperature is in the range 45℃ to 70℃, the actual COP is only 0.6 to 0.8 times as same as the Rankine cycle heat pump[3].

The practice high grade input energy is used as the base to determine the actual COP，and the work consumption of flue gas to overcome the fluid resistance is considered. When the flue gas pressure lift is controlled between the range 1000Pa to 2000Pa，the most consumption of work is about 1w per 1m^3 flue gas. Fig. 8 is the plot of compression ratio against evaporation temperature. The gross temperature lift is higher and the compression ratio is higher, the ratio drops along with the evaporating temperature increasing. Fig.9 shows the relationship of actual COP against the gross temperature lift and evaporating temperature, along with the temperature lift increasing the actual COP drops obviously, if the lift increases 5℃ the actual COP will decrease about 0.5. The evaporating temperature has a little influence on the actual COP.

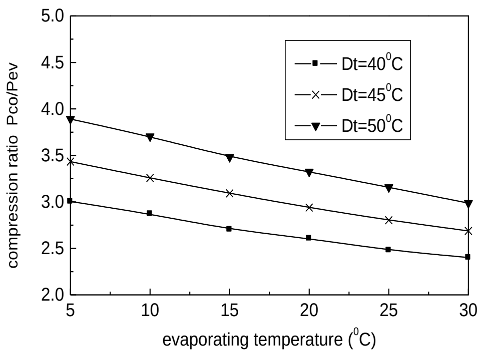


Fig.8 compression ratio against evaporation temperature

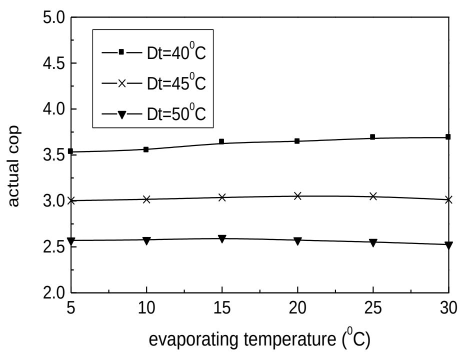


Fig.9 actual COP against evaporation temperature

If the technical flow chart (Fig.5) is used in practice engineering the actual average COP is greater than or equals 3. It can save 10%~20% energy of natural gas when the emission flue gas temperature drops from the range 100℃～200℃ to 30℃～40℃ for different air factors. It is very important to increase the thermal efficiency and decline the consumption of natural gas.

5 CONCLUSIONS

According the combustion theory, fist law of thermodynamics and the gas law, analyses are made on the dew temperature, saturated humidity and enthalpy of flue gas of combusted natural gas.

The calculating equations for these parameters are derived and the corresponding calculation results are given in patent of curves, which can be used as the base for actual engineering design.

A new technical flow is put up that have a waste heat boiler and three parallel heat pumps. Basing on the new technical flow the COP of each heat pump can exceed 3. If the decrease of temperature drops from high temperature 100℃～200℃ to low temperature 40℃～30℃,the use of the sensible heat and latent heat of partial condensation can be at a high level, and the thermal efficiency of natural gas can be raised 10%～20%.

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