RENEW OF THE THERMAL ENERGY OF MULTIPHASE FLUIDS BY COMPRESSION-CONDENSATION SYSTEM

A. Chisacof

Mechanical Engineering Faculty, University "POLITEHNICA" of Bucharest,
313, Spl. Independentei, RO – 77206 Bucharest, Romania; chisacof@itcnet.ro

ABSTRACT

The large amount of used fluids which is released every day in the atmosphere by the industrial plants and current activity, could modify, in the medium to long term the local climate, and this could, in different ways, strongly impact the human activities. Concerning the emission from the industrial plants, especially from the power plants and chemical layout, which use the important quantities of fossil fuels and row materials, the important amounts of fluids containing the vapour-gas mixture, having a low or moderate temperature (in the range of 100 °C to 250 °C), are evacuated into the surroundings. The limitation of this negative impact may by realised by an advanced recovery of available heat of the multiphase mixture, and also by the condensation of vapour components from gas-vapour system. In this mode a part of the pollutant or of the reusable fluids, may be stored in the special reservoirs or recovered, and reinserted in the technological layout.

In this paper is proposed a combined system for the advanced recovery of heat and of the condensable components from gas-vapour mixture. The proposed system consists in the initial compression of the gas-vapour mixture in aim to increase the mean temperature and the dew point of the medium. On this way, the level of temperature during the heat transfer processes increases, the amount of recovered heat increases too, due of the heat of condensation extracted from the vapour phase. By this system we find the possibilities to use its thermal energy by co-generation in the own plant, or in the other cooling, refrigeration or heating systems. The dry gas obtained after the condensation is expanded in a turbine. On this way a reduction of external work input for compression is realised.

The paper presents the range of the efficiency of the proposed system in function of the mixture composition, of the compression ratio. The evolution of the recovered heat and of the mass fraction of recovered liquid is presented, in function of initial composition of gas-vapour mixture

KEYWORDS

Condensation, compression, vapour-gas mixture, multiphase fluid, co-generation.

1. INTRODUCTION

Technological processes, especially from chemical and energy plants, have to satisfy the restrictive economic and environmental criteria. These deals may be reached using the internal co-generation of the energy and recovering the renewable materials. Coupling these processes an important enhancement of overall efficiency of technological layout is expected.

In the plants mentioned above, we have the important flow rates of working fluids in different phases. From the specific technological processes the large amounts of used fluids, called often "waste" fluids and are released every day in the atmosphere. We observe today an important modification of the local or zone climate in the medium to long term, and this could, in different ways, strongly impact the human activities [1]. Concerning the emissions from the industrial plants, which use fossil fuels and row materials, the "waste gas" evacuated into the atmosphere, represents in fact the gas-vapour mixture having a medium or low temperature (usually in the range of 100 °C to 250 °C). Often, these fluids have, before the entrance in the evacuation system of the plant, an important gage pressure(see ref. [2] and[3]). From the gas-vapour mixture analysis we observe that the vapour molar fraction is usually in the range of 15% to 35%. Due of the important hydrogen content in fossil fuels or of the initial moisture contains by row materials, in the waste gas the water vapour molar fraction is important. On the other hand, the moisture in the surroundings increases significantly which may affect occasionally even some technological processes, being necessary the supplementary dry systems. Excepting the water vapour from the waste gas, an important content of carbon dioxide exists in this. Actually, the problem of captivation, transformation in liquid and ice, and to store this component, represents a priority in the environmental protection (see ref. [1] and [2]). By freezing the carbon dioxide the important sensible and latent heat may be obtained, but the temperature is very low and it is difficult to use it. Also, a certain degree regarding the utilisation of this thermal energy in other devices must be take into consideration.

Actually, in the heating or power systems, the recovery of heat is realized until in the vicinity of the water dew point, but the fraction of condensed vapour is reduced and the mean temperature of exhausted gas is above the dew point. In fact, the partial condensation of vapour occurs only in the sublayer of the heat transfer boundary layer and the bulk temperature of the gaseous phase is greater than the dew point temperature [4].

In this work we propose a mixed system of compression-condensation of the gas-vapour mixture, in aim to have an advanced recovery of heat, especially of the latent heat of condensable component. Different modules in the heating or reheating processes of the technological layout may use this quantity of heat, having an acceptable temperature of the mixture. The scope of the compression of gas-vapour mixture, is to obtain an augmentation of the mean temperature of mixture during the heat transfer process. Consequently, an important quantity of recovered heat results from the latent heat due of the vapour condensation.

2. ESTIMATION OF GAS-VAPOUR HEAT CONTENT

Taking account of the above assumptions, we may consider the waste gas as two main components fluid, the one being the condensable component (i. e. water vapour) and another is represented by the non-condensable component (i. e. mixture of perfect gases or dry gas).

Reference state of the mixture will be considerate at the exit of the technological plant, or at the inlet in the proposed heat recovery system. Consequently, the properties and parameters of fluids will be specified by the subscript “**r**”. The calculus of the evolution of thermodynamic properties of gas-vapour mixture was developed in [3] and [5]. The molar enthalpy of vapour-gas mixture above the dew point temperature is:

$$H_M = (1 - Y_{vr})\, H_g + Y_{vr}\, H_r \qquad (1)$$

And the molar enthalpy of the mixture, only the gaseous phase, below the dew point becomes:

$$H_M = (1 - Y_{vr})\, H_g + Y_{vr}\, (H_v - \beta\, r_v\, M_r) \qquad (2)$$

Where H_g and H_v represent the molar enthalpy of dry gas and of vapour; $\mathbf{r_v}$ is the latent heat of vapour; M_v – molar weight of vapour. The condensed liquid fraction **β**, which appears below the dew point temperature of mixture, is given by the relation:

$$\beta = 1 - \frac{p_v(1 - Y_{vr})}{Y_{vr}(p - p_v)} \qquad (3)$$

where $\mathbf{p_v}$ represents the saturation pressure of vapour corresponding to the temperature mixture and **p** is the total pressure of mixture. We observe that for **β** = 1 the vapour is totally condensed.

The evolution of molar enthalpy of gas-vapour mixture in function of temperature, at different values of initial vapour fraction of mixture is shown in Figure 1. We observe that an important amount of heat is obtained under dew point temperature $\mathbf{T_s}$ (i. e. T_s = 60,02 °C for Y_{vr} = 0,2). It is known that the dew point temperature increases with the vapour fraction. The non-condensing gas is considered having the dry air properties, which is the case of the majority of the flue gases obtained by the burning processes. The heat obtained by the partial condensation of vapour has an important amount, but unfortunately the temperature level is low, and its use in the regeneration systems, is drastically limited. On the other hand, we observe that the amount of renewable heat increases with the vapour fractionY_{vr}, and the mean temperature of mixture in the condensation zone too.

Figure 2 shows the corresponding evolution of condensate fraction β in function of the temperature and initial vapour concentration $\mathbf{Y_{vr}}$. At a certain temperature, for example at 40 °C, the biggest value of β is obtained for the high vapour fraction at the inlet in recovery system $\mathbf{Y_{vr}}$. Consequently, for the high value of $\mathbf{Y_{vr}}$, we have a high values of renewable thermal energy at a high mean temperatures.

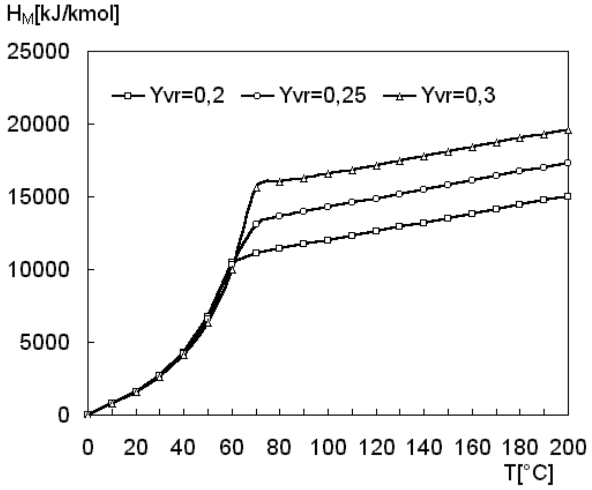

Figure 1. The influence of vapour fraction Y_{vr} of the molar enthalpy of mixture (p= 1 bar)

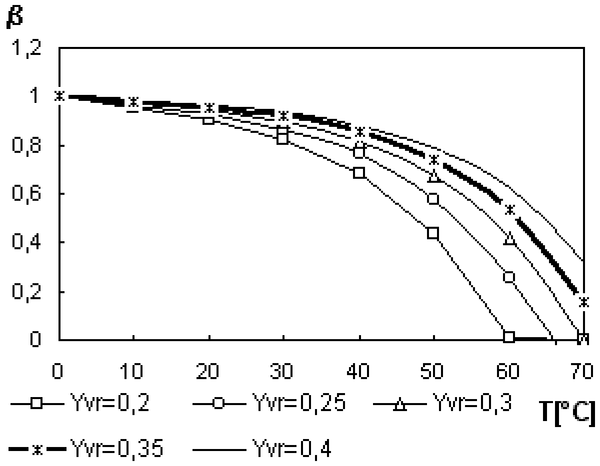

Figure 2. Condensed liquid fraction β versus temperature at different initial molar vapour fraction Y_{vr} (p = 1 bar)

The influence of mixture pressure is also significant. At the high values of mixture pressure **p** the amount of recovered heat increases significantly. Figure 3 shows the evolution of renewable heat, only for gaseous phase. The temperature values of the cooling interval are from 180 °C to 40 °C at 1 bar of mixture pressure. We observe that the total recovered heat **q_t** and the heat recovered during the condensation process **q_{cd}** rise with the molar vapour fraction **Y_{vr}** and with the mixture pressure. It is very interesting to observe that the difference between the recovered heats for the two pressures is practically the same for the condensing zone. That implies that quantitatively, the mass of condense, obtained supplementary at the high value of pressure mixture, is not a function of vapour fraction Y_{vr}. As a secondary effect, due of the rise of dew point temperature with the pressure, the sensible heat of condense liquid increases too.

The influences of the molar vapour fraction **Y_{vr}** pressure mixture and of the **p** on the condensate fraction β are shown in the Figure 4 and Figure 5. We remark that at low values of mixture pressure and molar vapour fraction, the values of condensate fraction are strongly affected.

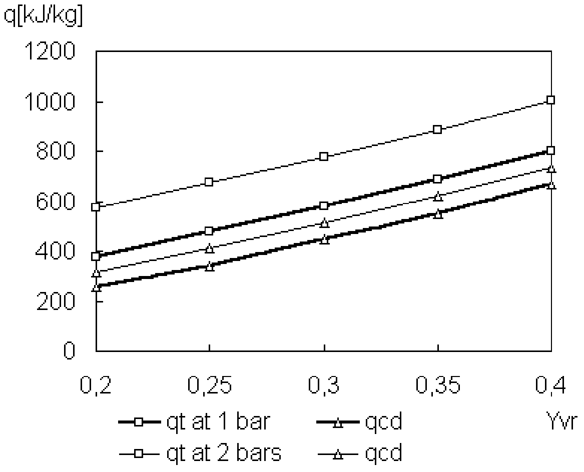

Figure 3. Evolution of recovered heat in function of vapour fraction Y_{vr} at different total pressures (from 180°C to 40°C)

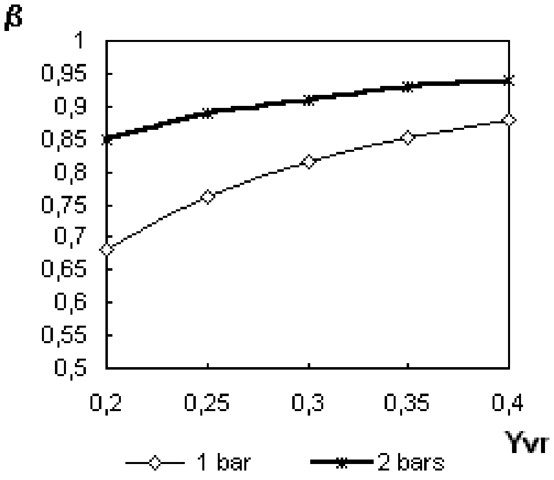

Figure 4. Condensed liquid fraction β versus vapour molar fraction mixture Y_{vr} at different pressures

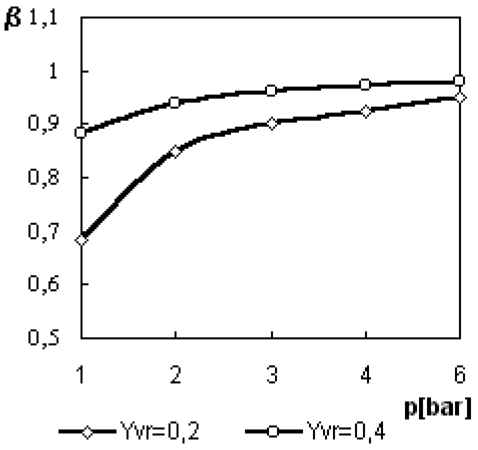

Figure 5. Condensed liquid fraction β versus mixture pressure p at different molar vapour fraction Y_{vr}

These advantages of the compression-condensing processes are displayed on the Figure 6 and Figure 7. Figure 6 shows that due of the initial compression of the dry mixture, the temperature increases, and consequently, the enthalpy of the mixture, the dew point temperature, the amount of sensible heat and of the recoverable heat in the condensing zone, increase too. For the data employed in this example, for compression ratio of 2, the effective input work for compression $|w_{k_{ef}}|=150$ kJ kg^{-1}. The corresponding amount of recovered heat is of 197 kJ kg^{-1} (the range of temperature for the recovered heat is from 180 °C to 40 °C at a mixture pressure **p** = 1 bar). Also, we have a rise of dew point temperature from 60,02 °C to 75,88 °C and the corresponding growth of the condensation fraction β varies from 0,68 to 0,848.

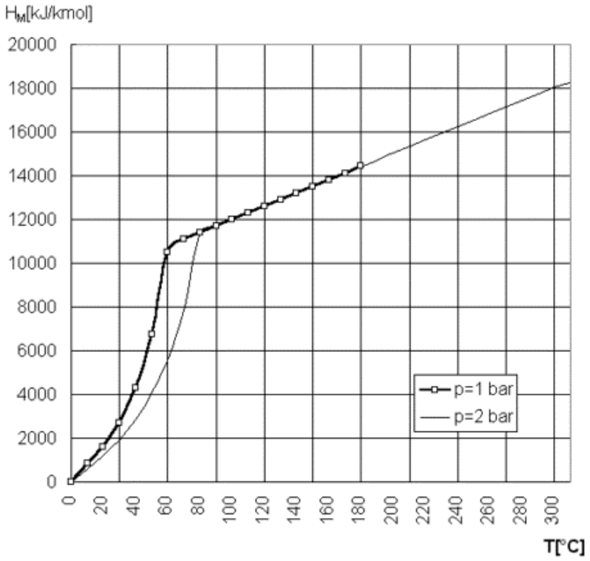

Figure 6. Molar enthalpy of gaseous phase at different compression pressures (Yvr= 0,2)

A. Chisacof, chisacof@itcnet.ro

Figure 7 shows the evolution of mean temperature in the condensation zone versus mixture pressure, for two values of initial vapour fraction $\mathbf{Y}_{\mathbf{vr}}$. It is obvious that at the high values of mixture pressure, we obtain the high values of mean temperature in condensing zone and consequently, the degree of recovered heat increases too. Another effect of the compression process is represented by the reduction of evacuated vapour in the surroundings. It is known often, that the vapour may have the negative impact on the environment. Hence, by reduction of the vapour quantity evacuated into the surroundings, the pollution with this component diminishes.

All these advantages may be exploited by an adequate recovery system of thermal energy from waste gas. It is recommendable to include this system in the technological plants (see [2] and [5]).

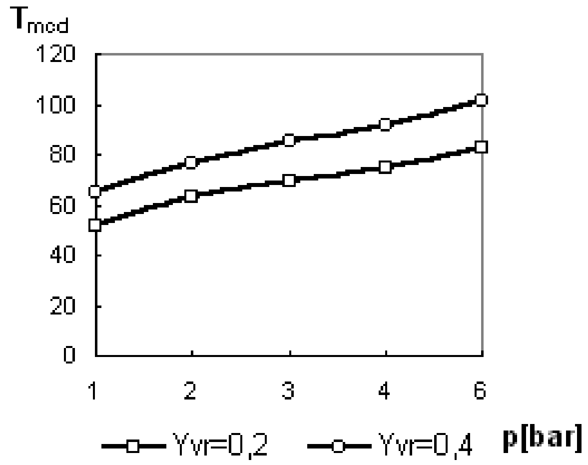

Figure 7. Mean temperature in the condensation zone versus mixture pressure p

3. ADVANCED COMPRESSION-CONDENSING SYSTEM OF HEAT RECOVERY

As we have seen above, in aim to increase the efficiency of heat recovery from the multicomponent fluids with condensable component, and to reduce the pollution effect of different components, the following methods are recommendable:

- the rising the pressure of gas-vapour mixture
- the enhancement of initial vapour concentration in the mixture, if it is possible, for example by the suction of waste vapour provided by different modules of the plant
- the use of drop separators to move the liquid phase and consequently, to dry the gas;
- introduce the adequate parameters of cooling fluid to reduce the exergy losses
- the internal co-generation is preferable
- use the potential energy of the dry gas by injection in the adequate point of the technological layout of the principal plant, or by expansion in a turbine
- include the proposed heat recovery system in the plant layout, combining it with the heating and cooling systems, which are often met in the energy or chemical plants.

Taking into consideration these exigencies, we have proposed the diagram of the advanced heat recovery system, shown in Figure 8. The waste gas coming from the boilers or other technological modules, is mixed with the waste vapour, if it exists, and is introduced in the compressor **K**. Due of the compression, the temperature of mixture increases and the difference between this and the dew point temperature increases too (see in the Figure 6 the enthalpy evolution for the mixture pressure of 2 bars). On the Figure 6 we observe a rise of sensible heat of the mixture. Than, the mixture is driven to the condenser **CdI** of the first stage of heat recovery system. Here, due of the high temperature of the principal fluid, a partial vaporisation of the cooling fluid may occurs (in the case of low pressure of the cooling fluid, i. e. water at the atmospheric pressure). The multiphase mixture outgoing from condenser is introduced in the drop separator **DSI**, and after separation, the liquid phase is introduced in the liquid cooler **CLI**, where its sensible heat is recovered. The gaseous phase leaving the top of the separator **DSI** is driven to the second stage of the heat recovery system. Here, another condensation occurs in the condenser **CdII**. The cooling liquid does not change the phase in this module because the mixture has a moderate temperature. Than, in the drop separator **DSII,** the separation of gaseous phase and liquid phase takes place. The recovery of sensible heat of liquid phase is realised in the liquid cooler **CLII**. In the heat recovery system it is preferable to use the water as cooling liquid, instead of gas (i. e. air), because the heat transfer coefficient for the liquid is greater than for the gas. On this way we may have a reduced difference of temperature at pinch point. Consequently the exergy losses diminish.

The gaseous mixture leaving the drop separator **DSII**, at low temperature and at a pressure greater than the atmospheric pressure, has a reduced fraction of vapour. In the realised example, at 40°C the molar vapour fraction in mixture is 3,7% for Y_{vr}=0,2 and 3,8 for Y_{vr}=0,4. Hence, we may consider the outgoing mixture from DSII as a dry gas. Figure 9 shows the evolution of the mixture temperature and the corresponding molar enthalpy in the heat transfer modules, for the proposed heat recovery system.

The dry gas outgoing from the second drop separator **DSII**, may be used in the specific technological processes (chemical or drying plants), as is shown by the case **A** (Figure 8). Another possibility is to use the dry gas in the expansion turbine **T** (Figure 8, case **B**). In this case the outlet temperature of gas from the turbine is often under the surrounding temperature, and it may represent a working fluid for refrigeration systems. Actually, the emission of carbon dioxide in the environment rises, and the captivation of this component, in the liquid phase or as CO_2 ice, becomes to be an important method to reduce its impact [1]. In this situation the gases evacuated from the turbine may represent the first stage of the carbon dioxide liquefaction plant.

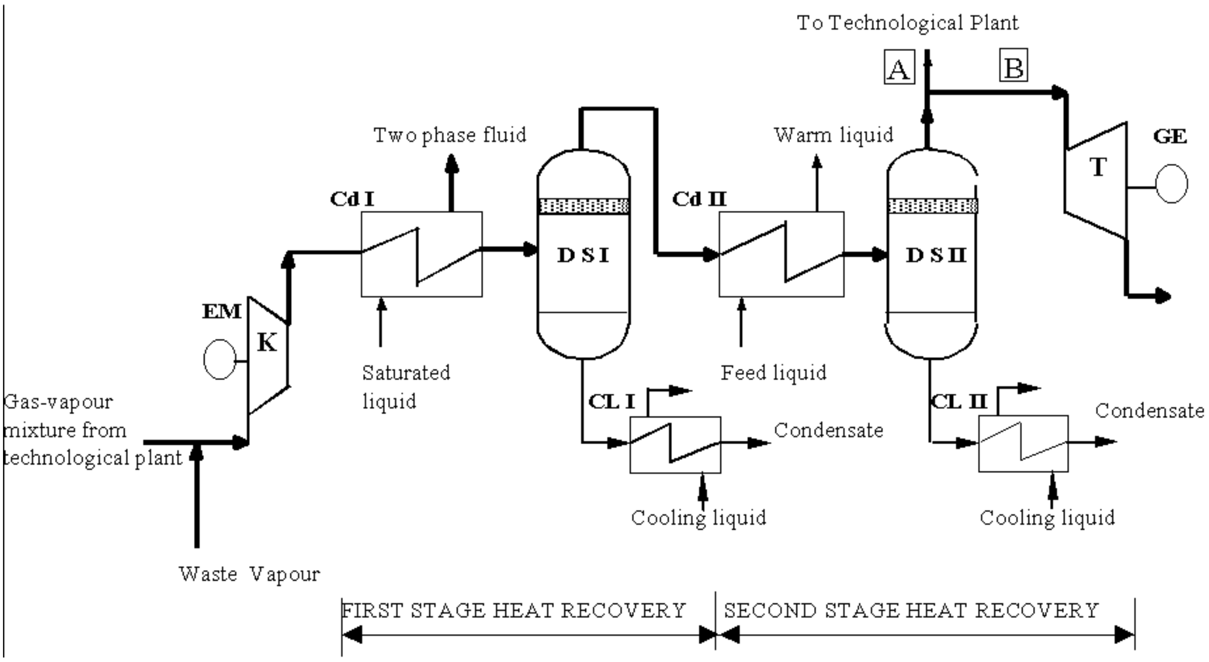

Figure 8. Schematic heat recovery system using latent heat of condensable com ponent K - compressor; Cd I - first stage condenser; DS I - drop separator I; CL I - liquid cooler I; T - expansion turbine; Cd II - second stage condenser; DS II - drop separator II; CL II - liquid cooler II

In the case when the dry gas is evacuated into the atmosphere the impact of vapour diminishes significantly. By the separation process of carbon dioxide in liquid phase or ice phase, the negative effect at the high levels of the atmosphere reduces too.

4. THE EFFICIENCY OF COMPRESSION – CONDENSING SYSTEM

The compression of the gas-vapour mixture involves consumption of work. An electric or mechanical device as a motor or turbine (Figure 9) may drive the compressor **K**. The effective compression work, for 1 kg of inlet mixture [6], is:

$$|w_{Kef}| = (h_{kr} - h_r)/\eta_{mk} \qquad (4)$$

where h_{kr} represents the specific enthalpy at the exit from the compressor, h_r is the specific enthalpy at the suction section of the compressor and η_{mk} is the mechanical efficiency of the compressor, $\eta_{mk}=0{,}98$.

The effective work obtained by the gas expansion in the turbine **T** is:

$$w_{Tef} = g_{dg}\, c_{pdg}\, T_{dg}\, [1-(p_o/p_{dg})^{(k-1)/k}]\, \eta_{iT}\, \eta_{mT} \qquad (5)$$

where g_{dg} represents the mass fraction of dry gas mixture resulted after the vapour condensation, c_{pdg} is the specific heat of dry mixture during the expansion in turbine, T_{dg} is the dry gas mixture temperature at the inlet in turbine, p_{dg} – pressure of dry gas mixture at the inlet in turbine, p_o – the pressure of the surrounding, η_{iT} – internal efficiency of the turbine, $\eta_{iT}=0{,}77$, and η_{mT} – mechanical efficiency of the turbine, $\eta_{mT}=0{,}99$. Consequently, the net specific work input in the compression-condensing system results:

$$|w_{efs}| = |w_{Kef}| - w_{Tef} \qquad (6)$$

The efficiency of utilisation of the net specific work in the heat recovery system is defined similarly with the coefficient of performance for the heat pump (see [7] and [8]), and represents the ratio of recovered heat to the input of work in the system, hence:

$$\varepsilon_{COPS} = q_t/|w_{efs}| \qquad (7)$$

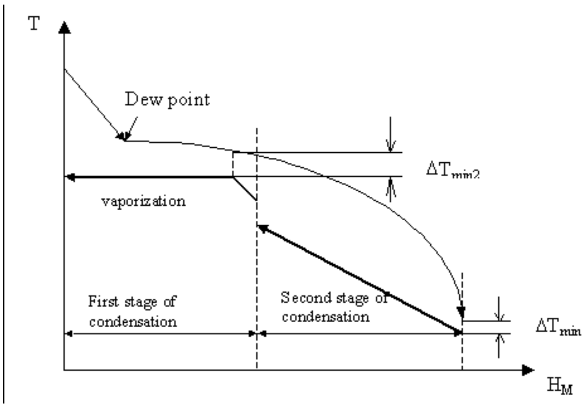

Figure 9. Temperature - enthalpy diagram for heat recovery system

A. Chisacof, chisacof@itcnet.ro

The evolution of the efficiency ε_{COPS} is represented in Figure10. We observe an important rise of ε_{COPS} for the high values of vapour inlet fraction $\mathbf{Y}_{vr}$. This fact occurs due of the important enhance of the recoverable heat, especially by the amount of latent heat released during the condensation, in comparison with the moderate rate of growth of the net specific input work.

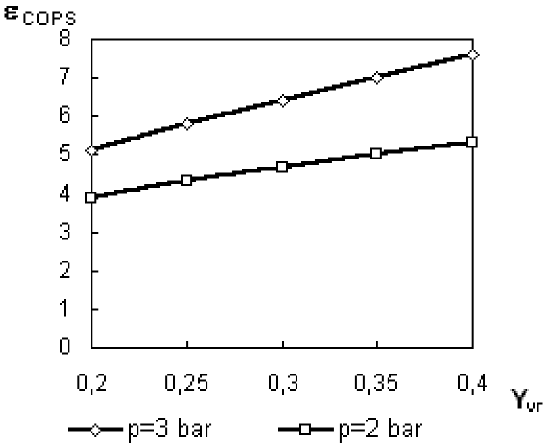

Figure 10. Efficiency evolution of the heat recovery system versus mixture pressure

5. CONCLUSIONS

The recovery of sensible and especially of the latent heat of condensable components from the gas-vapour mixture represents an important way to improve the efficiency of heat recovery systems.

The input of compression work in the system leads at an important enhancement of the recoverable heat having an acceptable temperature, which allows an efficient regeneration of heat.

The augmentation in vapour fraction of mixture gives the high values of recovered heat and of the mean temperature during the heat transfer processes.

Combining the initial compression of gas-vapour mixture with the suction of the available low-pressure vapour, the high rates of liquid fraction are obtained by condensation, and the dry gas results from the proposed heat recovery system. Also, the pollution of the surroundings with vapour diminishes drastically.

Without a recovery of heat, the expansion of the dry gas in the turbine has as result a reduction of the net input work in the proposed system, and an important increase of the coefficient of performance of proposed is realised. A secondary utilisation of the exhausted gas from turbine in refrigeration modules is recommended.

Using the proposed advanced heat recovery system by its adequate integration in the technological layout, the overall efficiency of this increases significantly. In some technologies the liquid phase, obtained by vapour condensation is renews too.

References

[1] Jaud, P., Faut-il piéger le gaz carbonique émis par les centrales thermiques ?, Epure, ed EdF Division Récherche et Développement, pp 24-32, n° 64, Octobre (1999)

[2] Chevennement, E. and Ronco, T., L., La gazéification intégrée à un cycle combiné. ?, Epure, ed EdF Division Récherche et Développement, pp 100-113, n° 64, Octobre (1999)

[3] Chisacof, A. and Marinescu, M., Recovery systems of low level thermal energy from sources with non-linear characteristics, FLOWERS' 94, Proc. of the Florence World Energy Research Symposium, pp 63-69, SG Editoriali Padova Italy (1994)

[4] Botsh, T., W. and Stephan, K., A model to describe the steady-state and dynamic behaviour of vertical condensers fed by mixtures, Revue Générale de Thermique, vol. 36, pp 481-491, Paris (1997)

[5] Chisacof, A., Analyse thermodynamique des systèmes de récupération de l'énergie à bas potentiel thermique, JETC IV, Actes des 4es Journées Européenne de Thermo-dynamique Contemporaine, Nancy France, pp 249-255 (1995)

[6] Baehr, H., D., Thermodynamik, 6th ed., Springer-Berlin (1988)

[7] Bejan, A., Advanced Engineering Thermo-dynamics, John Wiley Sons, New York, (1988)

[8] Feidt, M., Thermodynamique et optimisation énergétique des systèmes et procédés, TEC et DOC, Paris (1988)

[9] Schmidt, E., Properties of water and steam in SI units, Springer-Berlin (1969)

Nomenclature

c	specific heat, kJ kg^{-1} K^{-1}
h	specific enthalpy, kJ kg^{-1}
H_M	molar enthalpy, kJ kmol^{-1}
w	specific work, kJ kg^{-1}
M	molar weight, kg kmol^{-1}
p	pressure, bar
q	heat, kJ kg^{-1}
r_v	latent heat, kJ kg^{-1}
T	temperature, K
Y_v	vapour molar fraction

Greek symbol

β	weight condense fraction
ε_{COPS}	coefficient of performance of compression condensing system
η	devices efficiency (compressor or turbine)

Subscripts

cd	condense	m	mechanic, mean
dg	dry gas/mixture	M	molar
ef	effective	o	environment
ev	evacuated	r	reference state
g	gas	t	total
i	internal	T	turbine
K	compressor	v	vapour

A. Chisacof, chisacof@itcnet.ro

RENOUVELER L'ÉNERGIE THERMIQUE DES FLUIDES POLYPHASIQUES PAR UN SYTÈME DE COPMRESSION - CONDENSATION

RÉSUMÉ. *Des grandes quantités de fluides sont évacués tous les jours dans l'atmosphère par les soit par les usines, soit due aux activités courantes, ce qui peut modifier le climat en ayant un fort impact sur les activités humaines. En ce qui concerne les émissions données par les grandes plates-formes industrielles, en spécial par les usines chimiques et les centrales électriques, consommateurs des importantes quantités de combustibles fossiles, les fumées évacuées dans l'environnement contiennent des fractions élevées de vapeur d'eau à basse ou moyenne température (dans l'écart de 100°C à 250°C). Dans le but de réaliser une limitation significative de cet impact négative sur l'environnement, est nécessaire d'introduire dans la chaîne industrielle des installations de récupération avancée de la chaleur contenue dans les mélanges polyphasiques par la condensation de la vapeur contenue par ceux-ci. Dans cette manière une partie de fluides polluants est récupérée, même réutilisé, peut être stocké dans les réservoirs ou réintroduite dans la chaîne technologique.*

Dans ce travail on propose un système combiné pour la récupération avancée de la chaleur des composants condensables du mélange gaz-vapeur. Le système proposé utilise une compression initiale du mélange gaz-vapeur, ce qui a comme but l'augmentation de la température moyenne et de celle du point de rosée du milieu. Par conséquent, on obtient un niveau élevé de la température du milieu pendant le déroulement de processus de transfert thermique et d'autre part, due à la condensation de la vapeur, la quantité de chaleur récupérée augmente aussi. Le système proposé permet l'utilisation de la chaleur par co-génération dans l'installation elle-même, respectivement dans d'autre système de chauffage ou de réfrigération. Les fumées sèches, issues de système de compression-condensation, sont détendues dans une turbine. Par cette méthode on diminue l'apport de l'extérieur de travail mécanique nécessaire à la compression du mélange diminue.

Dans le travail sont données les valeurs de l'efficience thermique du système proposé en fonction de la composition du milieu et de taux de compression. Aussi, sont présentées les évolutions de la chaleur récupérée et de la fraction de liquide obtenue par condensation en fonction de la composition du mélange.

Mots clés: *condensation, compression, mélange gaz-vapeur, fluide polyphasique, co-génération.*

A. Chisacof, chisacof@itcnet.ro