CHEMICAL ENGINEERING TRANSACTIONS, Volume 12, 2007
Edited by Jiri Klemeš

The investigation of vapor condensation in horizontally oriented channels with cross corrugated walls

Perevertaylenko O.Yu., Nagorniy E.R.[1], Tovazhnyanskyy L.L.[1], Kapustenko P.O.[1]

AO "Sodrugestvo–T", Krasnoznamenniy per. 2, k. 19, Kharkiv 61002, Ukraine; tel.: +380577202278 e-mail: pau@kpi.kharkov.ua
[1]Centre for Energy Saving Process Integration, National Technical University "Kharkiv Polytechnic Institute", 21 Frunze St., Kharkiv 61002, Ukraine, tel/fax: +380577072223, e-mail: kap@kpi.kharkov.ua.

The problem of heat transfer for flows in channels of plate heat exchangers with cross corrugated walls is very complicated, especially relating to two phase flows. The subject of the investigation is the process of vapor condensation in horizontally oriented channels formed by corrugated plates. The corrugation of plates is complicated and consists of different patterns. The experimental investigations were carried out for single phase flow in channels under investigation and for condensation of pure vapor and vapor containing non condensable gases. Appropriate relationships were obtained. The results of investigation were used for development of special plate heat exchanger for condensation column of ammonia synthesis unit, where the condensation of synthetic ammonia occurs. The manufactured plate unit was installed into existing condensation column. The results of industrial tests are in good agreement with experimentally based relationships used for calculations and design of the plate heat exchanger.

1. The subject of investigation

The efficiency of plate corrugation is the most valuable factor in the design of optimal plate heat exchangers. It was proved in investigations of single-phase heat transfer and also for condensation (Tovazhnyansky and Kapustenko, 1984; 1996). There are several works dedicated to condensation process in channels with cross corrugated walls for steam condensation, as well as for multi component mixtures condensation (Palm and Thonon, 1999: Thonon and Bontemps, 2002; Tovazhnyansky et.al.,2004). The investigations indicated the increased values of heat transfer coefficients comparatively with condensation process inside plain tubes. But the majority of investigations were carried out for traditional vertical position of plates according to design of industrial plate condensers. As was emphasized by Srinivasan and Shah , 1997, the orientation of condensation surface is extremely important.

This work is dedicated to investigation of condensation process in special all welded plate unit designed to work at high temperature and pressure conditions of ammonia production plants. Such design was developed especially for use in ammonia synthesis columns for heating of fresh gas mixture that is going to catalyzer bed with outgoing hot gas that is leaving catalyzer bed after reaction. The duty parameters are as high as temperature up to 525° C and pressure up to 32 MPa. The successful implementation of such plate heat exchangers in ammonia synthesis columns lets to decrease the volume of heat exchanger inside column and to increase the volume of catalyst. It gave the possibility to increase the ammonia output on 15%.

Another perspective implementation of special plate heat exchanger in ammonia synthesis plants is its installation in ammonia condensation column. Its duty is preliminary cooling of ammonia containing gas before ammonia separation with cold gas after separation that is returning to ammonia synthesis column. The schematic drawing of condensation column is shown on Figure 1.

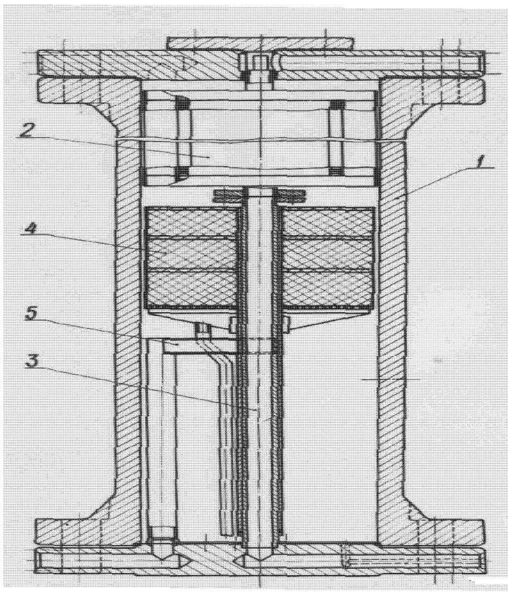

Figure 1. The schematic drawing of condensation column: 1- high-pressure vertical shell with two covers; 2 - heat exchanger; 3 - outlet pipe; 4 – separation basket; 5 - horizontal jet.

The gaseous mixture with temperature 30÷35°C after preliminary separation come to heat exchanger where it is cooled to 15÷20°C and partial condensation of ammonia occurs. Then gas is going to evaporator and after evaporator returns to the column with small content of liquid ammonia. The liquid ammonia is separated after stream injection through jet 5 and the rest of liquid ammonia is separated in basket 4 filled with Rashing bodies. Then ammonia free gas is going to heat exchanger with temperature 0…2°C where it is heated up to 20÷25°C and goes to ammonia synthesis column. The process pressure is about 29÷32 MPa.

Design of plate unit was adopted similar to design of plate heat exchanger for ammonia synthesis column. It consists of a number of horizontally oriented corrugated circular plates (Fig.2) welded in pack so that several passes on each stream are obtained, each pass consist of a number of inter plate channels. The flow arrangement is cross flow inside one pass and total counter flow for all unit. The original “three chevron” corrugation is aimed to achieve even distribution of flow and heat transfer parameters around the surface area of the plates.

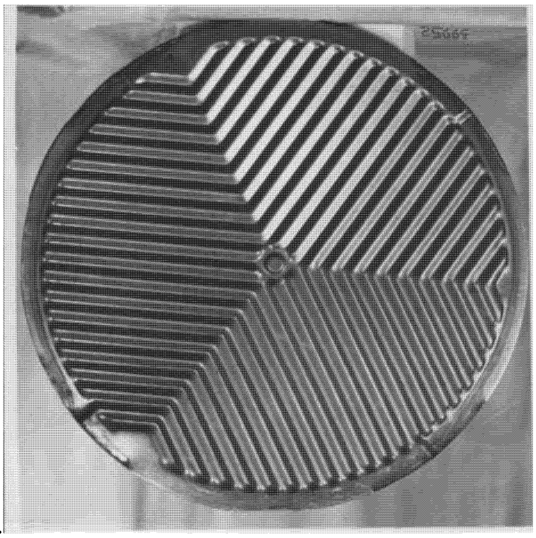

Figure 2. The corrugated plate of heat exchanger (Photo)

2. Laboratory and on site tests

The experimental investigations were carried out for laboratory test unit and for industrial plate heat exchanger installed into existing condensation column of ammonia synthesis plant. The laboratory tests were carried out for test sample that consists of four corrugated plates (Fig. 2) welded in two couples and compressed between two massive covers. Three identical channels with cross corrugated walls were formed. The central channel was used for hot (condensing) flow, upper and bottom channels were used for cooling water circulation. The plates for test sample were of the same size as for existing condensation column with inner diameter 600 mm.

The parameters of corrugation are: height of corrugation h=5 mm, shortest distance between adjacent corrugation ribs S=18 mm, angle between adjacent chevrons axes φ=120ºC. The test sample was disposed horizontally. For the measurement of temperatures of flows and upper and bottom walls of the central channel thermocouples were used. The experiment was carried out in three modes, namely:

1. Heat transfer in single phase flow.

2. The simulation of ammonia condensation from gas vapor mixture. The saturated steam is mixed with preheated air and after superheating on 1÷2ºC the mixture is supplied to central channel. In this mode average velocity of air steam mixture was 4÷6 m/s, average specific heat flux was $(13\div30)10^3$ W/m^2, volumetric part of steam in mixture was 0.1÷0.4.

3. The investigation of saturated steam condensation without air addition. The testing parameters were as follows: inlet pressure of saturated steam 100÷200 kPa, average velocity of steam in channel 14÷30 m/s, mass velocity of steam flow 10÷25 kg/m^2·s, temperature difference "steam - wall" 9÷26ºC, heat flux through condensation surface (1÷5)W/m^2 ·10^5 .

The industrial unit was the plate heat exchanger with heat transfer area 82 m^2, which consisted of 492 plates, six passes on each side and forty passages (channels) per each pass. Average cross flow area of one channel was 0.00158 m^2.
The composition of hot and cold gas mixtures are presented in Table 1.

Table 1. Composition of hot and cold flows through industrial plate heat exchanger, % vol. (pressure P=29÷32 MPa)

Component	Hot gas mixture	Cold gas mixture
Ammonia	4÷6	2÷3
Nitrogen	21÷22	20÷21
Hydrogen	50÷58	59÷64
Argon	7÷5	5÷4
Methane	8÷7	4÷8

The flow rate of hot gas mixture was (60÷65) · 10^3 normal m^3/h, the flow rate of cold gas mixture was (54÷59,5) · 10^3 normal m^3/h.

3. Results and discussion

The condensation of gas mixtures containing vapors is the process with significant variation of its intensity and values of parameters along heat transfer surface and detailed calculations are possible only with local characteristics of the process. As it was shown earlier (Tovazhnyansky and Kapustenko,1984), in case of high gas mixture velocities the calculation of local parameters is possible with the help of modified heat momentum and mass transfer analogy, based on correlations for single phase flow. The data of experiments for heat transfer in single phase flow gave the following empirical correlation:

$$\mathrm{Nu} = 0.097\,\mathrm{Re}_m^{0.73}\,\mathrm{Pr}^{0.43}\ , \tag{1}$$

where Nu is the Nusselt number; Re_m – Reynolds number; Pr – Prandtl number.
The correlation for friction factor in single phase flow:

$$f = 2.5\ \mathrm{Re}_m^{-0,25}\,. \tag{2}$$

The results of pure steam condensation for experimental pattern were estimated for upper and bottom plates respectively. The influence of specific heat flux on average film heat transfer coefficient was described in form h=f(q), where h – film heat transfer coefficient from condensing steam to appropriate plate (W/sq.m.K), q – specific heat flux value (W/sq.m.).
The following correlations were obtained for upper and bottom plates respectively:

$$h_u = 3.11 q_u^{\ 0.7} \tag{3}$$

$$h_b = 0.0013 q_b^{\ 1.3} \tag{4}$$

If is evident that for upper and bottom plates the variation of film heat transfer coefficients are of different character. Such difference may be explained with weak influence of steam flow velocity on condensate film located on bottom plate, as

comparatively low thermal resistance of condensate film on upper plate is significantly higher for bottom plate.
The increase of steam velocity results in decrease of thickness of condensate film on bottom plate and h_b increases. When the steam velocity increases to the value that corresponds to specific heat flux $q=4{,}3 \cdot 10^5$ W/sq.m., the condensation process on upper and bottom plates become identical and single equation may be used for both plates:

$$h = 0.64 q^1 \tag{5}$$

The enhancement of heat transfer from condensing flow by corrugated walls was proved too. The industrial tests show on high overall heat transfer coefficients, 1100÷1200 W/ ($m^2 \cdot K$) and more full condensation of ammonia. The compactness of plate heat exchangers inside condensation column let to increase the volume of separation basket in the column.

4.Conclusions

The heat transfer for vapor condensation from gaseous mixtures is maintained at the same high level of enhancement as in the case of the heat transfer in a single phase flow. The features of condensation on surface of top and bottom corrugated walls were explained. The equations for heat transfer and pressure drop were obtained and used for design of industrial unit. The industrial tests demonstrated the enhancement of ammonia condensation process in condensation column with plate heat exchanger.

Acknowledgements

The support by EC project SHERHPA (contract No COLL-CT-2004-500229) is sincerely acknowledged.

References

Tovazhnyansky L. L. and Kapustenko P. O., 1984, Intensification of Heat and Mass Transfer in Channels of Plate Condensers. “Chemical Engineering Communications;, v. 31, No. 6., p. 351-366.
Palm B. and Thonon B., 1999, Thermal and Hydraulic Performances of Compact Heat Exchangers for Refrigeration Systems, Proceedings of the International Conference on Compact Heat Exchangers and Enhancement Technology for the Process Industries, Banff, Begell House, New York.
Tnonon B., Boutemps A., 2002, Condensation of Pure and Mixture of Hydrocarbons in a Compact Heat Exchangers ; Experiments and Modelling. “Heat Transfer Engineering”, , v.23, No. 6, p. 3-17
Tovazhnyansky L. L., Kapustenko P. O., Nagorna O. G., Perevertaylenko O. Yu ., 2004 , The simulation of Multicomponent Mixtures Condensation in Plate Condensers. “Heat Transfer Engineering”, v. 25, No.5, p. 16-22
Srinivasan V. and Shah R.K., 1997, Condensation in Compact Heat Exchangers, Journal of Enhanced Heat Transfer, 4 (4) pp. 237 – 256.