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Failure Analysis of Methanol Evaporator

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***Abstract*—**Thermal water hammer is a special type of water hammer which rarely occurs in heat exchangers. In biphasic fluids, if steam bubbles are surrounded by condensate, regarding lower condensate temperature than steam, they will suddenly collapse. As a result, the vacuum caused by an extreme change in volume lead to movement of the condensates in all directions and their collision the force produced by this collision leads to a severe stress in the pipe wall. This phenomenon is a special type of water hammer. According to fluid mechanics, this phenomenon is a particular type of transient flows during which abrupt change of fluid leads to sudden pressure change inside the tube. In this paper, the mechanism of abrupt failure of 80 tubes of 481 tubes of a methanol heat exchanger is discussed. Initially, due to excessive temperature differences between heat transfer fluids and simultaneous failure of 80 tubes, thermal shock was presupposed as the reason of failure. Deeper investigation on cross-section of failed tubes showed that failure was, ductile type of failure, so the first hypothesis was rejected. Further analysis and more accurate experiments revealed that failure of tubes caused by thermal water hammer. Finally, the causes of thermal water hammer and various solutions to avoid such mechanism are discussed.

***Keywords*—**Thermal water hammer, Brittle Failure, Condensate thermal shock

I. INTRODUCTION

ETHYLENE and ethane products in Olefin plant produced with the temperature of -104 °C and pressure 1.0 bar, and temperature of -30.4 °C and pressures 9.5 bar respectively are stored in liquid storage tanks. Both products are used in the gas phase where the ethylene is used as the basic feed in Poly Olefin and the ethane product is used as supplementary feed in cracking furnaces. For the conversion of ethylene and ethane from the liquid to gas phase, steam with temperature of 175 °C and pressure of 5.8 bar is used. Regarding the low temperature of liquid ethane and ethylene and the high freezing point of water the probability of freezing of water is very high; therefore methanol is used as an interface heat transfer fluid between steam, ethane and ethylene. Based on the design, the liquid methanol in methanol evaporator with temperature of 110 °C and pressure 4.5 bar is changed to vapor phase in an isotherm process. This methanol vapor is poured into ethylene and ethane evaporators. With the loss of latent ethylene and ethane evaporators. With the loss of latent heat the vapor turns into liquid and is returned to the methanol evaporator. This process is done continuously in a closed cycle as shown in Fig. 1.

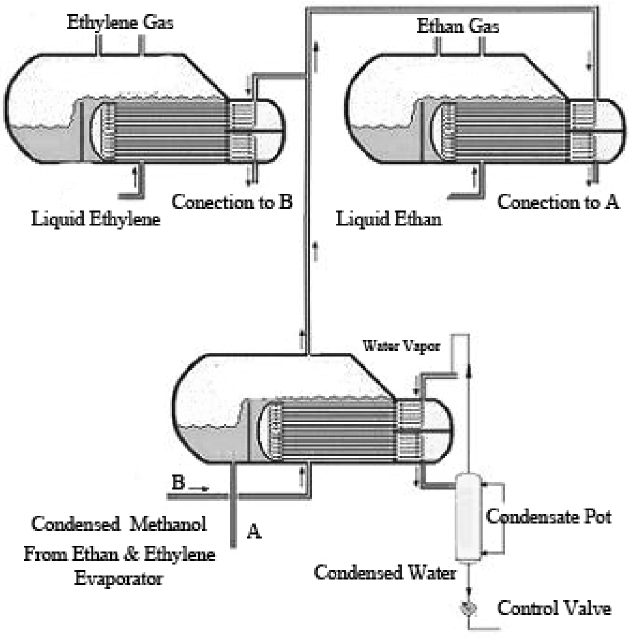

Fig. 1 The Methanol-Cycle

The methanol evaporator with a heat transfer area of 300 m² is designed .the evaporation of methanol to the level of 105 t/hr and ethylene evaporators have been designed for ethane phase change. This enables the phase change of ethylene with the capacity of 169 t/hr and an ethane evaporator with a capacity of 121 t/hr. Methanol evaporate based on standard TEMA is an exchange of BKU type [1] and Contains 481 tubes made of A-334 Gr6 with 19.05 mm diameter and a thickness of 2.11mm. This material is low temperature carbon steel and has the ability to be used at low temperatures down to -45 °C [2]. Sudden failure of the 80 tubes from the methanol evaporator tubes cause it to be out of service and due to the lack of access to failure sections. At first it was thought that the failure was due to thermal shock. According to accelerate time to launch, new tube bundles with the same properties and materials were replaced; but shortly afterwards failure reoccurred. To investigate the failure mechanism, hardness testing, chemical analysis, mechanical and metallurgical property evaluation, stress calculation, and examination of fracture morphology and appearance of failure sections were done. This eventually found that the cause of failure was thermal water hammer because of the low probability of this phenomenon occurring and of the relative ease of preventing it. The unspecified size and geometric shape of the trapped vapors in condensate and the difficulties in calculating the damage of so much stress has complicated this study.

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II. OBSERVATIONS

All tubes selected for the study have the same form of failure. Fig. 2 (a) and (b) shows the samples of failures.


(a) (b)

Fig. 2 (a) The exterior view and (b) the internal view of failure, As captured by a Video Bore scope

There were no abnormal corrosion products around and inside the failure sections, and the location of failure of damaged tubes in a particular area had not been longitudinal. Effect of brittle fracture that initially was thought to be thermal shock was not seen because this type of tube failure could have been caused by a sudden change in temperature. The other characteristics of the fracture were surface bulge and swell, and there was the short length crack at the head. As Fig.2 also implies the failure to cross is in the swollen form, which means the change of plastic deformation occurred prior to failure. This means the failure is ductile fracture and therefore chemical interactions or thermal shock can be completely ruled out. Generally, tubes failure occurs due to several causes. Therefore, the following investigations were performed in order to find the causes of failure.

III. EXPERIMENTAL TESTS AND DISCUSSIONS

A. Tube material study

Experiment to determine the chemical composition using spectrometry method Samples selected according to ASTM E-415[3] standard spectrometry method was applied to determine the chemical composition.

TABLE I
RESULTS OF CHEMICAL ANALYSIS OF SAMPLES

Element	*C*	*Mn*	*P*	*S*	*Si*
Sample 1	0.14	0.75	0.01	0.004	0.28
Sample 2	0.16	0.85	0.01	0.006	0.25
Sample 3	0.19	0.79	0.01	0.004	0.23
Std	0.3 Max	0.29-1	0.2 Max	0.025 Max	0.1 Min

Table I shows a chemical composition of the samples that match with the ASTM A334 Gr.6 standard. Hardness testing based on ASTM E-10[4] standard using Brinel method was performed on the samples. Table II shows the results. According to ASTM A334 GR.6 standard the maximum hardness shall not exceed than 190 HB.

TABLE II
HARDNESS OF SPECIMENS

Sample	Hardness			Hardness Average
	Point 1	Point 2	Point 3	
Sample 1	145	148	148	148
Sample 2	135	155	145	145
Sample 3	156	149	134	146

Tensile test with the fixture were performed at room temperature on samples. Table III shows the results.

TABLE III
YIELD STRENGTH AND ULTIMATE STRENGTH OF SPECIMENS

Sample	Primary Level mm²	Yield Strength Mpa	Ultimate Strength Mpa
Sample 1	117.53	415	488
Sample 2	117.53	485	490
Sample 3	117.53	402	456
Std		Min 240	Min 415

To determine the energy absorption capability in plastic deformation and investigation of toughness of tubes the test must be shot in temperature - 45 °C and according to the ASTM E-23[5] standard but due to low tube wall thickness it was not possible to prepare the standard samples.

Flare Test and tabulate test according to ASTM A334 / ASTM A1016 [6] standards were performed on samples separately. The results showed there are no evidence of any failure during Flare Test with 25% rate of outer diameter tubes broad noted and tabulate test to as high as 12.6 mm

According to the results, samples were consistent in terms of the mechanical - metallurgical with ASTM A334 GR.6 standards, that is, the used materials were consistent with designed tubes in terms of chemical and mechanical properties.

B. Calculation of Stress Due to the Pressure in the Tubes

Fluid passing through the tubes is steam at temperature 175°C and pressure 5.8 bar. Response of all control systems on evaporator showed normal processes before the tube failure, with no increase in pressure. According to the vapor pressure and with regard as thin walled structures, the main stress on the tube wall was calculated as follow [7].

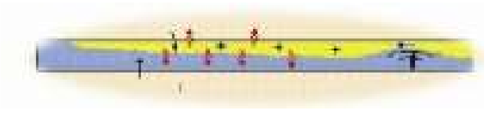
Longitudinal Stress	$Pr/2t = 1.31$ Mpa
Circumferential	$Pr/t = 2.62$ Mpa
Radial Stress	$P = 0.58$ Mpa

r: tube radius, t: tube thickness, P: steam pressure inside tube

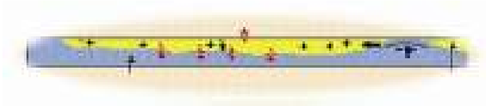
According to the theory of failure based on the criterion of maximum main stress, if tension that mutually crosses each other at certain temperatures exceeds the yield strength, failure will occur. As the above calculations show stresses imposed by fluid in the tubes compared to the minimum yield strength of the tube equal to 240 MPa. This is at the very low end and is negligible. Calculations based on Treska and Von Maiz criteria also confirm that stress imposed by the fluid inside the tube is approximately 1% of ultimate tensile strength of this type of steel. Therefore, such tensions cannot be considered as the cause of tube failure.

C. Local Stresses and Causes of Their Emergence

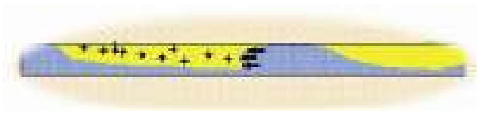
Failed tubes showed that imposed stress was more than the UTS of this type of steel, so whole process should be investigated and the results are to be compared with the design condition. Temperature of condensed returned methanol (lines A, B) must be 110 °C in accordance to the design, but in practice the lines suffered from freezing. The study showed the evaporators which were designed for evaporation of ethylene and Ethane with amounts of 169 t/hr and 210 t/hr respectively, according to the low need of the plant to consume these products were used lower than the design amount. It means that the amount of methanol used by these evaporators was lower than the designed load which was 105 t/hr these factors caused the pressure of the methanol closed cycle exceeds its design pressure and therefore caused the activation of the methanol pressure control valve. To prevent the valve action and the waste of methanol, the bulk of methanol evaporator tubes have been filled with condensate water. Consequently, both the heat transfer surface and the rate of vaporized methanol decreased Considering the low outlet amount of flow of vaporized methanol entering into the ethylene and ethane evaporator ,the temperature differences between heat transfer fluids was remarkable, (for example, in ethylene evaporator the temperature difference was more than 210 °C). It was very likely that the returned methanol from them with temperature much lower than the expected design temperature than the -20 °C. With these conditions, the line freezing was completely expected. There were special circumstances with the methanol evaporator where a major part of tubes were filled with condensate water and steam with pressure 5.8 bar. This pushed the water content a considerable amount of steam and water condensate were in contact together. Negative temperature of returned methanol increases the transferring of heat between water and methanol in the methanol evaporator. Sudden rapid phase change of steam bubbles trapped inside the condensate water in the tubes caused a sudden decrease of approximately 1200 times of vapor phase to the liquid phase [8]. Consequently, severe local pressure drop or even sudden vacuum formation lead to movement of the condensates in all directions, and it collusions that this collision applied severe stress in tube wall, this phenomenon is called thermal water hammer. Fig. 3 shows this process completely where excessive local tensions explain the failure mechanism.



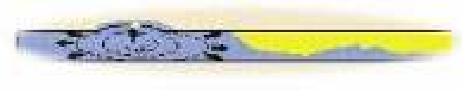
(a) Accumulation of condensate and create
Two - phase fluid into tubes



(b) Confinement of water vapor inside
The condensate



(c) A sudden phase change of water vapor trapped and
creates a vacuum



(d) Quick movement in condensed form to eliminate the vacuum,
dealing with each other and create tension on the tube wall

(e) Actual samples of the broken tube
Fig. 3 Various stages of formation phenomenon Thermal Water
Hammer In tubes

IV. CONCLUSION

According to the results of carried tests and calculations, no sign of corrosion products in the failed tubes were observed. The chemical analysis and mechanical - metallurgical tests showed that metal used in tubes were in accordance with standard ASTM A334 GR.6 and its properties in a way appropriate for use with low temperatures in the range of -45 °C. Calculations of stress due to the designed fluid pressure and temperature also indicate that stress imposed by the fluid inside the tube is less than 1% of ultimate stress. Therefore we cannot consider the operational temperature and pressure as the tube’s failure. The only remaining reason to justify the failure of the tubes was the thermal water hammer phenomenon. Although the failure mechanism of this phenomenon is almost certain. Unfortunately, stress caused by that cannot be calculated precisely due to the unknown geometry of trapped bubbles and flow. Experience shows that the stress caused by thermal water hammer depends on factors such as vapor pressure, temperature and size of the trapped bubble and temperature gradient of heat transfer fluid. In order to prevent the occurrence of thermal water hammer in tubes, different methods were studied. Studies showed that two main factors are responsible for this phenomenon. One of these factors is the condensate remaining in the tubes as a sub product of heat transfer. This creates two phase fluids. Overall, the deviation of thermodynamic cycle from the designed capacity will cause an unbalance cycle. In this case this is well observed. To prevent this diversion it is required that all relative exchangers used in service based on their designed condition or the cycle should be equipped with control systems for variable loads. Another factor that can take into consideration as secondary factor was the severe temperature gradient between the heat transfer fluids. This gradient causes a severe intensity of heat transfer rhythms by condensation rate that results in bubbles trapped in the condensate greatly increased. This causes a sudden, severe vacuum condensate stress to each other and on the inner tube wall. Therefore, the temperature gradient of the heat transfer fluids play an important role to reduce the temperature gradient on the methanol condensate return lines the methanol evaporator (lines A, B). Steam traces were embedded, which greatly reduces the heat transfer fluid temperature gradient and reduces the frequency of failure. However, the first factor remained constant and this time it was considered normal that failure continued but with less frequency and intensity. We can conclude that failure is caused by all of the above conditions. The more the level of critical conditions, the more failure occurs. As we observed, that first destruction caused the failure of 80 tubes. With the insertion of a steam trace, the subsequent destruction decreased to nine tubes.

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