INTERNATIONAL JOURNAL OF REFRIGERATION 55 (2015) 60–71

www.iifiir.org

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/ijrefrig

Dew point refrigeration systems: Normalized sensitivity analysis and impact of fouling

Osman K. Siddiqui [b], *Bilal A. Qureshi* [a], *Syed M. Zubair* [b,*]

[a] *Center of Excellence for Scientific Research Collaboration with MIT, KFUPM Box # 1276, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia*
[b] *Mechanical Engineering Department, KFUPM Box # 1474, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia*

ARTICLE INFO

Article history:
Received 7 November 2014
Received in revised form
18 February 2015
Accepted 12 March 2015
Available online 20 March 2015

Keywords:
Dew point refrigeration
Fouling
Sensitivity analysis
R22 alternate
System optimization

ABSTRACT

Compressed natural gas is transmitted through a network of pipelines after its production from oil-gas wells. This gas is then cooled below the dew-point to remove the condensate that may accumulate in the transmission line, causing erosion and deposits. In this paper, the dew-point refrigeration system used with a gas compression system is investigated. The design conditions are obtained from the manufacturer data sheets, which are validated with a computer program to study both the design and rating of such systems. The coefficient of performance (COP) of the system at the design condition is 2.81, while the effectiveness of condenser is 0.84 and that of evaporator is 0.91. The system COP sensitivity with regard to inlet single-phase temperatures, superheat temperature and conductance of heat exchangers (UA), is examined. It is found that the system is more sensitive under design conditions as compared to performance operations. The effect of fouling that degrades the UA value of the condenser and evaporator is also studied. It is found that condenser fouling has a significant impact on the performance of the system. The impact of alternate refrigerants at optimized intermediate pressure, is also investigated.

Systémes frigorifiques á point de rosée: Analyse de sensibilité normalisée et impact de l'encrassement

Mots clés : systéme frigorifique á point de rosée ; Encrassement ; Analyse de sensibilité ; Remplacement du R22 ; Optimisation de systéme

1. Introduction

Natural gas is efficiently transmitted from the production wells to the consumers, which is separated by long distances, using a network of pipelines. These transmission lines cannot be made straight due to the earth's topology, hence include changing elevations as well as twists and turns. The formation of liquid condensate (liquid dropout) in natural gas

---

[*] *Corresponding author*. Tel.: +966 13 860 3135; fax: +966 13 860 2949.
E-mail address: smzubair@kfupm.edu.sa (S.M. Zubair).

http://dx.doi.org/10.1016/j.ijrefrig.2015.03.014

Nomenclature

C	pipe factor (–)
$\dot{C}_{min}$	minimum value of the thermal capacitance rate (kWC^{-1})
D	pipe diameter (m)
e	density (lb$_m$ft^{-3})
f	friction factor (–)
h, H	enthalpy (Btulb$_m^{-1}$)
K	resistance coefficient (–)
$\dot{m}$	mass flow rate (kgs^{-1})
$\dot{Q}$	rate of heat transfer (kW)
t	temperature (°C)
UA	overall conductance (kWC^{-1})
V	velocity (m s^{-1})
$\dot{W}$	power requirement (kW)
Greek	
ε	heat exchanger effectiveness (–)
η	efficiency (–)
υ	specific volume (m^{3}kg^{-1})
Subscripts	
cd	condenser
cl	clean condition
cp	compressor
ev	evaporator
p	percentage change
sh	superheat
Abbreviations	
COP	coefficient of performance
LCV	level control valve
NSC	normalized sensitivity coefficient
PCV	pressure control valve

transmission lines happens due to the surrounding temperature being lower than the temperature of the gas leaving the plant (Hammerschmidt, 1934). During operation, the condensate may start accumulating in the lower bends. This (accumulated) condensate is of higher density. Due to the high pressure and velocity of gas, it would result in erosion and damage to the pipe. Additionally, the condensation of hydrates and water in the gas transmission lines results in formation of black powder deposits inside the pipeline. Dilawari and Saleemi (2008) presented profiling methods to predict the temperature and pressure within the pipeline so that regions susceptible to condensation may be identified. A white paper on liquid hydrocarbon drop out and its control was presented by Liquid Hydrocarbon Drop Out Task Group (2005). They made ten technical recommendations on controlling the liquid dropout based on the chromatic composition of the hydrocarbon and the tolerances available within the plant and ambient conditions.

For all practical purposes, Kern (1973) emphasized the importance of preventing this condensation by maintaining the gas inlet temperature and flow rate in addition to heating of the pipe sections, particularly in low temperature regions. The formation of natural gas hydrates can be suppressed by the addition of monohydric aliphatic alcohol, a volatile soluble solution. It results in formation of condensate with water that does not combine with hydrocarbons to form solid hydrates (Miller, 1941). The condensate accumulation in the pipelines is typically cleared by using pigging technology (McDonald and Baker, 1964) in which a pig is introduced into the pipeline without stopping its operation. The pig may be of spherical rubber material or a shaft with a seal along its circumference.

Brown et al. (2007) examined different models that are currently used in the industry for measuring the dew-point temperature of natural gas. Considering data of real gases, they showed that the difference between different models was no more than 2.5 °C, while some others showed slightly higher variability due to the assumption of synthetic mixture considered in their models. Bullin and Fitz (2011) presented a method to calculate the "practical" hydrocarbon dew-point specifications, where the term practical was used to represent the negligible amount of condensate (0.002 gallons of liquid per thousand cubic feet of gas) which would not have any significant impact on natural gas transmission system.

1.1. *Sensitivity analysis*

Sensitivity analysis is used to study the impact of different parameters on the system performance, thereby allowing us to identify the important factors. Normalized sensitivity coefficient (NSC) is especially helpful in allowing comparison between different parameters. The theoretical background for sensitivity analysis using uncertainty approach has been provided by Hodge and Taylor (1999). The uncertainty was normalized and used as normalized sensitivity coefficients (NSCs) and normalized uncertainties (NUs). Using this method, analysis of a cross-flow heat exchanger was carried out by James et al. (1995). They reviewed and developed the basic tools for uncertainty analysis. Qureshi and Zubair (2006) did uncertainty analysis on an evaporative cooler and condenser, including a step by step calculation of NSC for demonstration purpose. Area and effectiveness NSC as function of inlet and outlet process fluid temperatures and process mass flow rate, for varying mass flow rate ratio is studied. They concluded that for evaporative coolers under design conditions, process outlet temperature was the most significant factor for all the sensitivities. Under performance conditions, effectiveness is most sensitive to process fluid flow rate and process fluid inlet temperature. For evaporative condensers, the NSC values indicated that the condensing temperature is the most sensitive parameter. They reported that for a 72% increase in the inlet relative humidity, the normalized sensitivity coefficient for effectiveness increased 2.4 times, whereas for a 15 °C increase in the condenser temperature, it doubled. Chen and Tong (2004) performed sensitivity analysis for steady-state and transient heat conduction in functionally graded materials. They compared two solution methods and concluded that both are valid for evaluating the sensitivity of thermo-structural response of the materials.

1.2. *Fouling*

Cooling systems incorporate heat exchangers as a main component. Unwanted material deposition on the surface of