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Impact of ambient air temperature and heat load variation on the performance of air-cooled heat exchangers in propane cycles in LNG plants – Analytical approach

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ABSTRACT

An analytical method is presented to evaluate the air flow rate required in an air-cooled heat exchanger used in a propane pre-cooling cycle operating in an LNG (liquefied natural gas) plant. With variable ambient air inlet temperature, the air flow rate is to be increased or decreased so as to assure and maintain good performance of the operating air-cooled heat exchanger at the designed parameters and specifications. This analytical approach accounts for the variations in both heat load and ambient air inlet temperature. The ambient air inlet temperature is modeled analytically by simplified periodic relations. Thus, a complete analytical method is described so as to manage the problem of determining and accordingly regulate, either manually or automatically, the flow rate of air across the finned tubes of the air-cooled heat exchanger and thus, controls the process fluid outlet temperature required for the air-cooled heat exchangers for both cases of constant and varying heat loads and ambient air inlet temperatures. Numerical results are obtained showing the performance of the air-cooled heat exchanger of a propane cycle which cools both NG (natural gas) and MR (mixed refrigerant) streams in the LNG plant located at Damietta, Egypt. The inlet air temperature variation in the summer time has a considerable effect on the required air mass flow rate, while its influence becomes relatively less pronounced in winter.

1. Introduction

As global energy demand rises, natural gas plays an important strategic role in energy supply [1]. Natural gas accounts for about 24% of the world energy consumption [2] and is originally found as a gaseous fossil fuel [3]. Natural gas is the cleanest and most hydrogen-rich of all hydrocarbon energy sources and it has high energy conversion efficiencies for power generation [4,5]. Its popularity as an energy source is anticipated to grow considerably in the future as natural gas can help attain two significant energy goals; maintaining energy supplies necessary for economic and social developments and reducing adverse impacts on the environment in general [6,7]. The natural gas sector is poised for substantial growth over the next two decades and it is believed that it may even overtake oil as the prime fuel between 2020 and 2030 [4]. The evaluation and analysis of natural gas resources is vital for maintaining the natural gas supply [8]. At remote locations or when the distance between the gas market and the source is long enough, liquefying the natural gas for transport has been widely implemented as a major industrial operation as a practical solution in the energy industry [9]. The rational for liquefying natural gas is the huge reduction in volume thus, decreasing the size and cost of storage and transportation containers [10]. The evolution of global and regional LNG trade over the past twenty years has been a story of rapid growth, diversification and increased flexibility in LNG cargo movements [11]. For gas reserves that are remote from mature gas markets, liquefaction is often the only solution for gas exploitation.

There are a number of proprietary processes for natural gas liquefaction and even though each of the world's large base load liquefaction plants is unique in design, they all perform a basic common task: first treating the gas to remove impurities and then liquefying it by cooling to around 104–110 K [12]. A good understanding of design and operational requirements and efficiencies of natural gas liquefaction systems is essential for the success of the gas liquefaction plant. The real keys in developing a successful liquefaction plant are equipment selection and it's configurations to meet a plant's capacity goals [13]. The selection of a technology depends on different criteria, for instance it may be influenced by economic, environmental, financial, license or technical issues [14]. As stated, one of the most important challenges in natural gas

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Nomenclature

A_f	(fin surface area/m length), m^2/m
A_o	$(A_{po} + A_f)$ = (total outside surface area/m length), m^2/m
A_{pi}	(inside surface area of bare tube/m length), m^2/m
A_{po}	(exterior area of bare tube/m length), m^2/m
A_x	extended finned tube surface heat transfer area, m^2
APM	total extended tube external area/m length, m^2/m
APSM	ratio of external tube OD bare surface area to bundle face area, m^2/m^2
AR	(A_o/A_{po}) = ratio of fin tube area to exterior area of tube, m^2/m^2
$(C_p)_{air}$	specific heat of air, kJ/kg deg
$(C_p)_{propane}$	specific heat of propane, kJ/kg deg
CMTD	corrected mean temperature difference, °C
D_{eqv}.	equivalent diameter, m
F_t	cross flow correction factor
FA	face area, m^2
% free area	percentage free area
G_{air}	(air mass flow rate/free area), kg/m^2 s
h_i	inside tube film heat transfer coefficient, J/m^2 s deg
h_o	outside tube (finned-tube) heat transfer coefficient, J/m^2 s deg
h_{dirt}	fouling coefficient for inside of the tube, W/m^2 K
i	$\sqrt{-1}$, is the positive square root of minus one (imaginary number)
$I_o(x)$	Bessel function of the first kind of zero order
$I_1(x)$	Bessel function of the first kind of first order
J	J-factor (for heat transfer)
$(k)_{air}$	thermal conductivity of air, W/m K
$(k)_{aluminum}$	thermal conductivity of aluminum, W/m K
$(k)_{propane}$	thermal conductivity of propane, W/m K
$K_o(x)$	modified Bessel function of the second kind of zero order
$K_1(x)$	modified Bessel function of the second kind of first order
L	tube length, m
L_o	$(r_2 - r_1)$, fin height, m
MTD	mean temperature difference, °C
NT	number of tubes
Nu	Nusselt number
Pr	Prandtl number
Q	air-cooled heat exchanger heat load, J/s
r_{dirt}	$(1/h_{dirt})$ scale resistance, m^2 K/W
r_1, r_2	inner and outer radius of the circular fin, m
Re	Reynolds number
t_{in}	air inlet temperature, °C
t_{out}	air outlet temperature, °C
T_{in}	propane inlet temperature, °C
T_{out}	propane outlet temperature, °C
U_{ox}	extended surface overall heat transfer coefficient, J/m^2 s deg
W_{air}	air mass flow rate, kg/s
$W_{propane}$	propane mass flow rate, kg/s
y	fin thickness, m
$\Gamma(n)$	gamma function
θ	time, h
$(\lambda)_{propane}$	latent heat of vaporization of propane, kJ/kg
$(\mu)_{air}$	dynamic viscosity of air, mPa s
$(\mu)_{propane}$	dynamic viscosity of propane, mPa s
$(\mu_s)_{propane}$	dynamic viscosity of propane at tube surface, mPa s
ϕ	fin efficiency
ω	$(2\pi$/time period), frequency, s^{-1}

liquefaction plants is to improve the plant energy efficiency [15,16]. Some advances in the LNG value chain, covering upstream gas production and gathering, liquefaction, shipping and regasification processes were reviewed [17] and recent developments in the LNG processes with emphasis on commercially available refrigeration cycles were presented [18,19]. LNG plants consist of a number of parallel units called trains, which treat and liquefy natural gas and then send the produced LNG to storage tanks [20]. For any new plant development, selection of the appropriate liquefaction technology and associated equipment is very influential in reducing cost and increasing project feasibility [21]. Currently four major cycles are applicable for LNG production wherein the PPMRC (propane pre-cooled mixed refrigerant cycle) licensed by APCI (Air Products and Chemicals Inc.) is the dominant liquefaction cycle in LNG production [22,23]. This process accounts for a very significant proportion of the world's base load LNG production capacity and is the technology applied in the LNG plant located at Damietta, Egypt. Technological developments have been made which allow the increase in train capacity of the PPMRC cycle to be extended beyond 5 MTPA (million tons per annum) and the larger capacity AP-X liquefaction cycle increased beyond 8 MTPA. The AP-X cycle evolved from the PPMRC liquefaction process [24]. LNG plants consume an intensive amount of energy due to their relatively high production scale. Hence, any enhancement to the energy efficiency of LNG plants will considerably reduce natural gas consumption and CO_2 emission [25]. Previous studies showed that performance improvement is obtained and low grade energy is applicable for absorption refrigeration systems under air cooling conditions [26,27]. It was specified that the majority of the developed liquefaction processes included a pre-cooling cycle as an initial primary stage of the liquefaction process, where the natural gas is to be cooled to a temperature in the range of −30 to −50 °C [28]. As previously stated, one of the main differences between the pre-cooling stages of the existing LNG processes is the use of mixed or pure components as the refrigeration fluid [29]. However, it is more advantageous to use a single component refrigerant for pre-cooling in the mixed refrigerant processes such as in the propane pre-cooled mixed refrigerant process (PPMRC) by APCI [30]. Around 85% of the currently installed trains use pure propane as refrigerant in the pre-cooling cycle [31]. In the pre-cooling, a multistage refrigeration cycle is used at three or four pressure levels to exchange heat with the gas stream and the warm mixed refrigerant, cooling both streams down to around 238 K (−35 °C). In the liquefaction sub-cooling cycle the rest of the process takes place; there the natural gas is further cooled down from 238 K to around 113 K (−160 °C) by the mixed refrigerant [32].

The propane pre-cooled mixed refrigerant cycle (PPMRC) is the technology applied in the LNG plant located at Damietta, Egypt. This process accounts for a very significant proportion of the world base-load LNG production capacity. The pre-cooling cycle (Fig. 1) uses propane refrigerant to cool the process gas stream down to −35 °C and it is also used to cool and partially liquefy the MR (mixed refrigerant). The propane refrigeration system operates in a closed loop utilizing propane evaporating at four pressure levels; LP (low pressure), MP (medium pressure), HP (high pressure) and HHP (high high pressure), to supply refrigeration to the feed (NG) circuit and the MR circuit thus, cooling and partially liquefying the MR. Successive flashes to lower pressures provide each