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Exergy-based analysis of gas transmission system with application to Yamal-Europe pipeline

M. Chaczykowski *, A.J. Osiadacz, F.E. Uilhoorn

Warsaw University of Technology, Faculty of Environmental Engineering, Heating and Gas Systems Department, Nowowiejska 20, 00-653 Warszawa, Poland

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ABSTRACT

This paper presents a thermodynamic analysis of a gas transmission system consisting compressor stations and pipeline sections. It has been assumed that the compressor station comprises a gas turbine-driven compressor and a gas cooler, and the irreversibility of the processes associated with the gas transmission was investigated. The exergy method was used to determine the amount of work supplied to the components of the pipeline system and the amount of work that is lost during the gas transmission. For the case study, the Yamal-Europe pipeline is chosen. In this study, a nonisothermal, steady-state gas flow model was used for comparing the performance of the gas transmission system under different cooler operating set points. The pipeline flow and the compressor station processes were governed by the equations which include real-gas model based on virial equation of state.

1. Introduction

Gas transmission systems usually operate in the pressure range between 4 and 12 MPa, with typical nominal diameters 600–1400 mm, and compressor stations located every 100–140 km along the pipelines. The compressor stations rise the gas pressure in order to overcome the pressure drops resulting from the frictional gas flow in the pipeline. The compression of gas is usually performed in centrifugal or reciprocating compressors driven by gas turbines or electric motors. A side-effect of gas compression is an increase in gas temperature, which increases the pressure drop along the pipeline. As a result of a higher gas temperature, the mean specific volume of the gas in the pipeline increases, causing the gas velocity and the pressure drop in the pipeline to increase. In order to reduce the undesired effects of gas temperature rise, gas coolers are installed at the compressor station outlet, usually utilizing ambient air as a cooling medium. Gas cooling at the discharge of compressor station may also be necessary to protect the pipeline external coating.

Gas turbines installed in compressor stations are fueled by natural gas while air coolers are powered by electric energy, therefore an exergy-based analysis is used in this study to evaluate the quality of energy utilization in a gas transmission system.

Harrison and Dean [1] presented the variation of exergy expressed as the ratio of exergies transferred by mass E_{out}/E_{in} along the pipeline with two-phase steam-water flow from geothermal well. They concluded that the exergy ratio is a more useful concept than the static pressure change for comparing flow through pipeline components in this case, since it can be directly used to estimate the influence of hydraulic losses on the power available at the delivery point.

Exergy-based analysis of gas transmission system was carried out by Evenko [2]. One section of the gas transmission system with an arbitrary selected structure was chosen to assess the overall second-law efficiency of the gas transmission process. Compared was the efficiency of transmission of gas and power, assuming in the first situation an ideal gas model. However, the exergy balance was limited to full-load operation of the compressor station.

The objective of this study is to carry out an exergy analysis of the gas transmission system, which takes into account (i) the real gas behavior with compressibility factor, enthalpy and entropy as a function of pressure and temperature, (ii) nonisothermal model describing the pipeline gas flow, (iii) turbomachinery performance at off-design conditions. The influence of cooling the gas on the efficiency of the overall compression process in the transmission system is discussed.

2. Mathematical formulation

A gas transmission system consists two basic elements: a compressor station and a pipeline, which are the examples of an open system. A typical compressor station design, as shown in Fig. 1, consists of a turbomachine, i.e. gas turbine (GT) and gas compressor

* Corresponding author. Tel.: +48 22 660 50 57.
E-mail address: maciej.chaczykowski@is.pw.edu.pl (M. Chaczykowski).

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Nomenclature

A	area, m^2
B	second virial coefficient, m^3/kmol
C	third virial coefficient, m^6/kmol^2; heat capacity, W/K
c	heat capacity ratio
c_p	specific heat at constant pressure, J/(kg K)
c_v	specific heat at constant volume, J/(kg K)
E	exergy, J
e	specific exergy, J/kg
$\dot{E}$	exergy flow rate, W
D	pipe diameter, m
f	Darcy friction factor
g	the acceleration of gravity, m/s^2
h	specific enthalpy, J/kg
L	pipeline length, m
LHV	lower heating value, J/kg
$\dot{m}$	mass flow rate, kg/s
N	rotational speed, rpm
P	power, W
p	gas pressure, Pa
$\dot{Q}$	heat transfer rate, W
$\dot{V}_N$	volumetric flow rate at normal conditions, m^3/s (Flow rate $\dot{V}_N$ is shown in normal conditions of 101.325 kPa, 273.15 K)
R	specific gas constant, J/(kg K); conduction resistance for cooler pipe wall, K/W
s	specific entropy, J/(kg K)
T	gas temperature, K
T_s	temperature of the surroundings of the pipeline, K
U	overall heat transfer coefficient, W/(m^2 K)
v	gas specific volume, m^3/kg
w	flow velocity, m/s
x	distance coordinate, m; molar fraction, %
z	elevation, m; compressibility factor

Greek symbols

α	convection coefficient, W/m^2; angle between the direction x and the horizontal
ε	effectiveness of the heat exchanger
η_{is}	isentropic efficiency of the compressor
η_m	mechanical efficiency of the compressor
η_t	efficiency of compressor driver (gas turbine)
ρ	density of the gas, kg/m^3
φ	relative humidity

Subscripts

0	ambient air conditions
ac	air cooler
gc	gas compressor
gt	gas turbine
c	consumption
d	design value
f	fuel
gts	gas transmission system
N	normal conditions
p	pipeline
ref	reference conditions (Reference conditions are 101.325 kPa, 298.15 K)

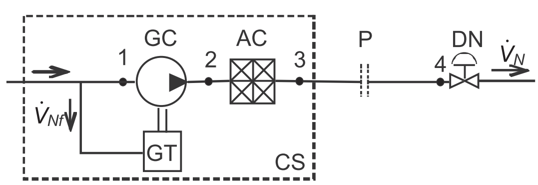

Fig. 1. Structure of the gas transmission system, CS – compressor station, GC – gas compressor, GT – gas turbine, AC – air cooler (after cooler), P – pipeline, DN – delivery node.

(GC), followed by a gas cooler, usually in the form of air cooler (AC). Mathematical model of the gas transmission system is represented be the set of equations describing thermal and hydraulic processes occurring in the pipeline and in the compressor station elements. The solution of the pipeline flow model under the assumption of steady-state conditions requires knowledge of boundary conditions, which are pressure, temperature and flow rate values at the inlet node of the system, and a setpoint values for the operating devices. The compressor station model is solved to allow for the accurate prediction of fuel consumption in the facilities.

Gas turbines and centrifugal compressors are the preferred means of compressing the gas. In a typical gas cooler, the heat from the gas is passed to the air in a forced-draft heat exchanger, in which one or more fans operate, depending on the actual flow rate in a gas transmission system and the number of compressors in service. Before the examination of exergy destruction and losses in a gas transmission system can be carried out, the basic elements of the system need to be modeled. In particular, the part-load performance of gas turbines and air coolers need to be modeled adequately.

The thermodynamic description of the elements of a gas transmission system in view of a variety of applications like transient gas flow simulation, compressor station sizing, and minimization of compressor driver fuel consumption is given in Ref. [3]. As a pipeline model, the transient nonisothermal compressible fluid flow model was used with the equation of state for a real gas. The compressor station model, however, did not contain any gas cooler component, and the calculation of discharge temperature was based on the assumption of an ideal gas model. The influence of real-gas effects on calculated compressor performance was studied by Ransom et al. [4]. They concluded that the ideal gas model can lead to significant differences in calculated compressor power and compression efficiency. The attempts to improve the accuracy of the compressor model by mixing real gas properties with ideal gas formulas were not recommended by the authors. The model developed in this study allows for a better prediction of the overall compressor and driver performance by using the real-gas model to determine the *p*-*v*-*T* behavior of natural gas during isentropic compression.

2.1. Centrifugal compressor

The compressor performance can be obtained from a detailed mathematical model based on conservation laws, or using the neural network approach. Jiang et al. [5] and Yu et al. [6] performed this type of research studies for centrifugal compressor and axial compressor, respectively. However, due to the complexity of the models and the amount of initial data required, in the general area of pipeline simulations the experimentally determined characteristic curves are commonly used.

The performance is usually displayed in a map showing isentropic efficiency and isentropic head as a function of gas flow rate