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Energy recovery from natural gas pressure reduction stations: Integration with low temperature heat sources

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ABSTRACT

Energy recovery from Natural Gas (NG) distribution networks is a promising strategy in order to pursue energy sustainability in urban areas. The NG pressure reduction process, normally achieved by means of conventional throttling valves, can be upgraded by implementing turbo expander technology, which allows recovery of energy from the NG pressure drop. As commonly known, in this process the NG must be preheated in order to avoid methane-hydrate formation. The preheating temperature represents a key parameter of the process, on which depends the possibility of integrating low enthalpy heat sources into the system and of exploiting more efficient technologies and renewable energies as well. In this work, the possibility of integrating a pressure reduction station with low temperature heat sources is studied. In particular, a novel plant configuration consisting of a two-stage expansion system is presented and its energy performances are investigated by means of numerical dynamic simulations. The risk of formation of methane hydrate is assessed for different operating conditions and for transient behavior. Finally, the energy efficiency of PRSs with high and low temperature configuration is compared, showing how the two stage expansion can achieve higher energy performance and be effectively integrated with low enthalpy heat sources.

1. Introduction

The European Union is strongly committed to policies for energy sustainability and Waste Energy Recovery (WER) in urban areas [1]. Natural Gas (NG) networks are a promising opportunity for widespread energy recovery in cities. The large extension of NG grids and the high number of NG Pressure Reduction Stations (PRS) present in the European territory allows the pursuit of an effective strategy to exploit the pressure drop from transportation pipelines to local networks, which is currently dissipated in expansion valves [2], converting this otherwise wasted mechanical energy into electricity by means of expanders (from here on, the WER acronym will refer to this kind of energetic conversion). For instance, there are about 416 PRS in Spain [2], while Austria and Denmark count about 40 main PRS each [3,4]. Moreover, a continuously increasing trend can be noticed inside and outside the EU, with a growing extension of the NG network and, correspondingly, of the number of PRS. In Turkey the number of PRS rose from 274 in 2010 to 320 in 2012 [5]. Therefore, there is a large WER potential in NG transmission grids, since from each station a non-negligible amount of energy can be recovered. Borelli et al. [6], for a given case study in Italy, estimated a potential WER of about 2.9 GWh/year for a total preheating need of about 3.1 GWh/year. Alparslan et al. [5] instead, estimated a potential WER of about 4.11 GWh/year for a maximum of 6.36 GWh/year of thermal preheating energy. Mansoor and Mansoor [7] defined an action program for WER in Bangladesh. Other examples of TE application can be found in Kostowski [8]. In this study, the system efficiency is about 60% and, according to the authors, positive economic results could be achieved with appropriate system design. The case study relative to the Khangiran refinery was presented by Farzaneh-gord in [9]. Here, the plant is capable of delivering a high amount of NG of about 390 kg/s. For this purpose, the electricity generation is designed to be about 7.5 MW which surely generates a non-negligible WER potential.

However, this option for energy recovery is not so obvious as might appear, since hard operating limits arise from the thermodynamic process happening when NG expands. In fact, for PRS functioning it is fundamental to maintain NG temperature above a certain threshold in order to avoid the formation of methane hydrates. These are solid compounds, resembling snow or ice in appearance and are formed with methane, ethane, propane, and isobutane in the presence of water at elevated pressures and temperature [10]. A description of the methane-hydrate formation mechanism was supplied by Koh et al. [11]. Ashouri

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et al. [12] calculated the minimum NG temperature at the inlet of throttling valves enabling avoidance of the formation of a solid phase. Among the methane-hydrate predictive models available in the literature, Khamehchi et al. [13] proposed a relevant predictive neural network model based on 356 experimental data.

This issue has traditionally limited energy recovery from PRS since the NG needs to be preheated before the expansion in order to produce electricity. This problem is usually solved by providing heat with a boiler or, in a better configuration, with a Combined Heat and Power (CHP) system [14,15]. Recently, a more advanced solution was proposed, which considers the actual expansion ratio β for NG in city gate stations [16]. As reported in [17], the typical β value is almost 5 but, in some cases, β ranges from 8 to 12, up to a maximum of 15. Some of these characteristic operating ratios enable the possibility of splitting the expansion process into two stages, and allows lowering the overall process temperature. In this way, due to the typical pressure operating ranges and geographical positioning, energy recovery from PRS represents a key opportunity for eco-industrial park development [18] and low temperature thermal process integration e.g. industrial microgrid networks [19] and 4th generation district heating networks [20] whose typical operating temperatures are about 50 °C. Moreover, the opportunity to lower the temperature enables the possibility of employing a wider range of heat production technologies, such as geothermal heat pumps or thermal solar panels [21–23], CHP, sewage water assisted heat pumps, heat pumps assisted from waste heat from manned spaces (e.g. underground air ventilation of waste air ventilation of big malls) whose usual supply temperatures currently range from 40 to 85 °C [20].

In general, the integration with district heating networks or waste heat sources in urban areas offers a noticeable opportunity for coupled energy recovery. Moreover, PRS operating schedule is directly linked to the NG users' demand, which leads to a spontaneous load matching between heating supply and demand in buildings, thus making the integration between PRS and district heating networks even more favorable. This integration of NG network with urban thermal grids, as well as the exploitation of a part of the large waste heat amount available inside cities, is a smart opportunity to improve urban energy recovery and to achieve a more effective energy use.

However, this smart and novel technology for diffused energy saving requires a further step in terms of system analysis and modeling, since the management of the low temperature heat coming from DHN or WER needs the plant to be adapted and controlled in a new way compared to the common integration with a CHP system. The purpose of this work is precisely to study the integration of PRS with low temperature heat sources. Energy performance of a typical low temperature PRS configuration was analyzed though numerical dynamic simulations. The results were compared to high temperature ones and energy benefits were estimated for a typical winter day. Furthermore, time-to-hydrates was assessed by considering the analytical predictive formulations of Motiee et al. [24], Mokhatab et al. [25] and Kidnay et al. [26].

2. System configurations

At first glance, energy recovery from gas expansion seems to involve positive aspects only and a large diffusion could be expected. Nevertheless, only few plants are currently in operation. Enthusiasm for this technological solution often collides with technical constraints and economic problems, mainly due to two different needs: guaranteeing safety when manipulating a flammable substance and preheating the gas, thus consuming fuel. Therefore, this kind of energy recovery system becomes less convenient not only from an energy viewpoint, but even from operating and economic ones. The opportunity to reuse waste energy or exploit existing heat facilities can move the balance towards a more efficient utilization of the NG pressure drop, fostering in this way the diffusion of expansion technology. In this sense, research on integrating low temperature heat sources in the PRS energy recovery systems is a key issue, which deserves to be deepened and analyzed well.

Table 1
NG composition at standard conditions (15 °C and 1 atm) [15].

Chemical substance	Weight composition [%]
Methane	92.347
Ethane	4.646
Carbon dioxide	0.568
Normal butane	0.133
Isobutane	0.102
Pentane	0.031
Isopentane	0.028
Helium	0.017
Propane	0.8
Nitrogen	1.319
Other hydrocarbons	0.009

One of the constraints that one must face in designing an energy recovery system based on NG pressure drop is methane-hydrate formation. Solidification of methane hydrates occurs when water molecules form a cage-like structure around smaller guest molecules (e.g. methane, ethane, propane, isobutane, normal butane, nitrogen, carbon dioxide, and hydrogen sulfide) [27]. Many studies have focused on methane-hydrate formation in natural gas pipelines. Considering the NG composition shown in Table 1 and a pressure of about 5 bar, three different mathematical correlations have been considered in order to identify methane-hydrate formation temperature. More precisely, by considering the correlations of Motiee et al. [24], Mokhatab et al. [25] and Kidnay et al. [26], methane-hydrate formation respectively occurs at temperatures of about −4.5 °C, −2.7 °C and −2.2 °C.

In general, this is a very challenging limit. Nevertheless, in urban areas or wherever possible, when properly managed it does not reduce the possibility of integrating a DHN or even an industrial waste energy source with the PRS to recover waste heat (also at low temperatures) in order to reach a higher level of efficiency.

However, it must be noticed that integration between the TE, which generates electricity from NG expansion, and the low temperature heater requires the adaptation of the system configuration in order to optimize its functioning and, ultimately, its control. For the purpose of analyzing the system behavior for different operating conditions and to find an effective set-up, two different plant configurations were analyzed and compared. A traditional set-up was studied, with a single TE like the one installed in the city of Genoa within the framework of the EU project CELSIUS (Combined Efficient Large Scale Integrated Urban Systems) [1], hereafter called "GE1 demonstrator" (Fig. 1). Then a low temperature integrated system was modeled. The GE1 demonstrator consists of a TE, capable of delivering a nominal power of 550 kW_e, whose design working flow rate is 22500 Sm^3/h, a slightly lower value than the average hourly flow rate of the PRS. The TE processes the NG from the national transport network, at a pressure of 24 bar_g, reducing its pressure to 5 bar_g.

Fig. 1 shows pictures of GE1 demonstrator, while Fig. 2 presents a simplified schematization of High and Low Temperature PRS Configurations, named respectively HTC and LTC: in brief, low temperature refers to two-stage expansion whereas high temperature refers to a single expander. In the high temperature configuration (Fig. 2a), the NG is preheated with a process water temperature of about 85 °C by means of a shell and pipe heat exchanger (H). The thermal energy is provided by means of two, standard, gas-fired boilers, which produce the hot water necessary to accomplish the NG preheating process. Referring to the low temperature configuration (Fig. 2b), the gas expands in two TEs in series and the process temperature is lower [28–31]. In this way, since the total NG pressure drop is split into two stages, the thermal preheating need at each expansion is lower. Also in this case, as described for the high temperature configuration, the NG is used as a

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