Energy Conversion and Management 101 (2015) 336–342

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Centrifugal compressor efficiency improvement and its environmental impact in waste water treatment

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ARTICLE INFO

Article history:
Received 16 January 2015
Accepted 25 May 2015

Keywords:
Centrifugal compressor
Energy efficiency
Life-cycle assessment
Waste water treatment

ABSTRACT

Energy costs typically dominate the life-cycle costs of centrifugal compressors used in various industrial and municipal processes, making the compressor an attractive target for energy efficiency improvements. This study considers the achievable energy savings of using three different diffuser types in a centrifugal compressor supporting a typical end-use process in a waste water treatment plant. The effect of the energy efficiency improvements on the annual energy use and the environmental impacts are demonstrated with energy calculations and life-cycle assessment considering the selected compressor task in the waste water aeration. Besides the achievable energy saving benefits in the wastewater aeration process, the presented study shows the influence of the additional material needed in the diffuser manufacturing on the total greenhouse gas emissions of the compressor life-cycle. According to the calculations and assessment results, the studied diffuser types have a significant effect on the compressor energy use and environmental impacts when the compressor is operated in the aeration task. The achievable annual energy savings in this case were 2.5–4.9% in comparison with the baseline scenario. Also, the influence of the additional material and energy use for manufacturing the diffuser are insignificant compared with the avoided greenhouse gas reduction potential.

1. Introduction

The ongoing growth in global energy use, mainly based on fossil fuels, has increased the concentration of greenhouse gases in the atmosphere [1]. The continued greenhouse gas (GHG) emissions have shown to result in temperature increase in the Earth's climate leading to a pressing necessity to reduce the emissions [23]. In addition to the radical transform of the current energy systems to carbon neutral systems, the increase in both production and end-use energy efficiency are among the key options to achieve the required GHG reductions [1,35,22].

Electric motors are responsible for the major part of the electrical energy use in industrial countries. In the EU, the share of electric motors is approximately 70% of the total electricity consumption [12]. Correspondingly, electric motor driven compressors are responsible for 18–25% of the industry's electricity use in the EU, which makes the compressed-air systems an attractive target for energy efficiency improvements [35,5].

Centrifugal compressors are widely used for example in process industry, oil and gas industry, waste water treatment, and refrigeration processes. The benefits of centrifugal compressors compared with axial compressor are often related to robustness, wide operating range, and relatively low investment and maintenance costs [37]. When considering the overall lifetime costs of the compressed-air equipment, the energy costs typically dominate the life cycle costs (LCC) [36]. According to Saidur et al. [36], the energy costs can be up to 80% of the total life cycle costs. An example of life-cycle costs of a compressor is shown in Fig. 1.

In general, the actual energy used in the end-process can be only a fraction of the required primary energy when the whole energy chain is considered [42,41]. Hence, the closer to the end-process the energy efficiency improvements are, the more effective they are in reducing energy-related emissions. In other words, the saved energy in the end-process can correspond multiple times over to the need of primary energy. Different options for this kind of improvements in compressor processes can be categorized for example into improvements in the efficiency of the system components, justified component selection and system dimensioning, and the energy efficient adjustment of the system output.

A typical end-use process for centrifugal compressors is biological waste water treatment, where compressed air is required especially in the aeration in active sludge tanks. In such waste water

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http://dx.doi.org/10.1016/j.enconman.2015.05.054
0196-8904/

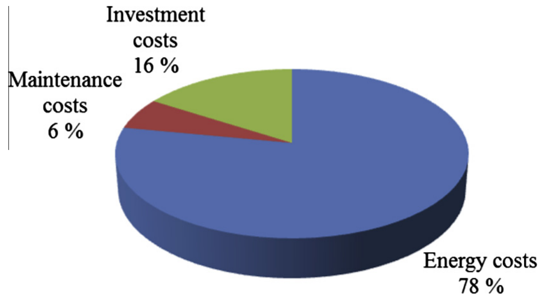

Fig. 1. Compressor life-cycle costs. The energy costs dominate the costs [36].

treatment plants, the aeration is typically the most energy-intensive process stage [3], and the compressors can be responsible for almost 70% of the total electricity use at the facility [6]. Typically, the aeration process is constantly alive, and as a result the annual downtime of the compressors is very low. Additionally, the required compressor pressure ratio is often constant. In the waste water aeration, the compressor discharge pressure is dictated mainly by the piping pressure losses and, more importantly, the water level in aeration tanks. These characteristics clearly demonstrate, not only the significance of the justified dimensioning of the system, but also the importance of the high compressor efficiency at the actual, required operation range.

Concerning the energy efficiency of a centrifugal compressor, the performance of a centrifugal compressor impeller has reached a very high level, and much of the potential for further improvements lie in the diffuser development as discussed by Kim et al. [28] and Issac et al. [24]. In general, there are three main types of diffuser designs: vaneless diffuser (VNLD), low solidity vaned diffuser (LSD) and vaned diffuser (VND), all of which have different influences on the overall compressor performance and the operating range. Correspondingly, all of these diffuser designs have varying material requirements in manufacturing; a point which is often not thoroughly considered from the life cycle point of view.

In this paper, these three diffuser types are studied from energy conversion and life cycle point of view. The main aim of the study is, not only to demonstrate the energy efficiency benefits of each diffuser type, but also to indicate the environmental impacts of these energy efficiency improvements in a compressor process. Therefore, the use of the different diffuser designs is studied in an example case consisting of a centrifugal compressor supporting the aeration process in a waste water treatment plant. For the assessment of the environmental impacts of the different diffuser designs, an LCA (life cycle assessment) study is conducted. The aim is to analyze (1) how much the improvement in energy efficiency of the compressor using different diffuser designs reduces the greenhouse gas emissions and (2) does the additional material needed in diffuser manufacturing have an effect on the total greenhouse gas emissions? Hence, the second research question can also be formulated as: Is improving the energy efficiency of a compressor reasonable if it requires more material in the compressor manufacturing?

Although this paper concentrates on energy efficiency improvements in the component design, the energy conversion of the compressor is not the only relevant indicator when evaluating the energy efficiency of the waste water treatment process or aeration stage. The overall energy efficiency is also affected for instance, by the dimensioning of the compressor system, leakages in the air ducts, distribution losses when delivering air into the tanks, and the efficiency of the aeration itself. In addition, the same compressed air delivered by the compressor units is typically used in many other process stages in the plant. As this study focuses on the energy use and the LCA study on compressor diffuser designs, other aspects affecting the aeration efficiency are excluded.

The paper is organized as follows: first, the energy efficiency improvement scenarios related to different diffuser designs are being discussed. The next section introduces a compressor task in a waste water treatment plant illustrating a typical end-use process for centrifugal compressors. The section also presents the resulting energy consumption and potential savings with each diffuser scenario. Based on these energy calculations, the life-cycle assessment study is conducted. Finally, conclusions of this study are given in the last section.

2. Studied efficiency improvement scenarios for centrifugal compressors

As mentioned, the centrifugal compressor performance can be affected with three main diffuser types: vaneless diffuser, low solidity vaned diffuser, and vaned diffuser. Additionally, the vaneless diffuser can be modified by pinch to improve the performance, which means narrowing the height of the diffuser compared to the impeller blade height. A schematic view of different diffuser designs is given in Fig. 2.

The presented diffuser designs can be studied in terms of efficiency improvement and material resource requirements. In this study, the presumed material for each diffuser scenario is aluminum (AlMg3). The diffuser scenarios are categorized into pinched diffuser (PND, Scenario 1), low solidity diffuser (Scenario 2), and vaned diffuser (Scenario 3). These three diffuser scenarios are compared with the selected baseline of the vaneless design (VNLD) of Scenario 0.

Scenario 1 represents the use of moderate pinch in the diffuser, where the diffuser passage height is narrowed from the nominal height. Pinched diffuser (PND) is known to improve the efficiency of a centrifugal compressor and still maintain an almost similar operating map width as a vaneless diffuser [25]. Scenario 2 considers the low solidity diffuser (LSD), where no geometrical throat is formed between the two vanes due to low number of short vanes. The LSD represents also higher efficiencies than the vaneless diffuser and it maintains the width of the operating map usually very well [16]. Although the vaned diffuser (VND) in Scenario 3 has usually the highest performance improvement of the different diffuser designs, the width of the operating map is clearly narrower than with the other designs. The narrower operating range is mainly due to two reasons: the diffuser vanes are sensitive to the changing incidence, and they form an aerodynamic throat, which limits the maximum mass flow. The incidence influences also the vanes in the LSD; however they are considered to be mostly guiding the flow instead of diffusing it and are therefore not that sensitive. In addition, the vanes in the low solidity diffuser do not form an aerodynamic throat; hence, the maximum mass flow is dictated by the impeller as in the vaneless diffuser.

In comparison with the vaneless diffuser Fig. 3 illustrates the efficiency improvements for different diffuser designs at the compressor nominal speed [19,21,2,29,9,34,27,26]. It can be interpreted from the figure that the average estimation for the efficiency by using pinched diffuser is 1.03 times the vaneless diffuser efficiency. For the low solidity diffuser and vaned diffuser the improvements are 1.04 and 1.05, respectively.

As mentioned, the main potential for efficiency improvements in centrifugal compressors lie in the stationary parts, as the impeller has been the most studied component in the past. Although the focus of this study is on the diffuser design, alternative improvement solutions can be found for example from the tip clearance. Increasing the tip clearance has a negative impact on the stage efficiency and the pressure ratio of the compressor [30,8,31]. Still, the impact of the increasing tip clearance on compressor efficiency can vary according to the compressor characteristics [43].