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Numerical simulation of novel axial impeller patterns to compress water vapor as refrigerant

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ABSTRACT

Through means of 3-D CFD (Computational Fluid Dynamics) method, a novel axial compressor with different impeller shapes compressing water vapor as refrigerant was investigated. The numerical simulation focuses on the fluid flow from compressor impeller inlet to outlet. The overall performance level and range are predicted. Different blade patterns with different hub sizes were compared regarding the aerodynamic performance. Independent of the blade pattern, in this numerical investigation the largest hub diameter shows the highest pressure ratio and efficiency at narrowest operating range.

1. Introduction

An application of the investigated preliminary compressor design is in mechanical compression refrigeration units that utilize water (R718) as refrigerant. The use of water as refrigerant in vapor compression system offers several potentially significant advantages and fulfills most of the fundamental requirements of a refrigerant [1]. The first main advantage of using water as refrigerant is because it is a green refrigerant; it is environment friendly, non-toxic and non-flammable. Besides these, as a green refrigerant it has zero ODP (ozone depletion potential) and zero global warming potential, which means there are no risks using water as refrigerant in the future. The second main advantage of using water as refrigerant is because it's be a green energy: it can be obtained for free and readily available; it also has no disposal problem; most importantly, it has a potential to save energy about 20–30% than conventional refrigerants [2].

However, compressing water vapor as refrigerant imposes specific challenges for the compressor designer. Fig. 1 compares the traditional refrigerant R134a to R718 and shows that this compressor needs to compress under vacuum environment varying between 900 Pa and 1800 Pa; Such a low pressure thus lower down density and produce a huge volume flow rate for compressors to handle [3]. In addition, the pressure ratio for water vapor as refrigerant has to reach about five which is roughly two or three times higher than conventional refrigeration cycles [2]. To achieve such as high performance, especially a high compression pressure ratio, it would be a big challenge for volume displacement compressors such as scroll compressors and turbo compressors are good candidates for the task.

Wight et al. [4] carried out a detailed scoping analysis of turbocompressor technology applied to steam compression in a water-based refrigeration cycle. Because of low efficiency (less than 75% for the radial bladed unit considered), huge impellers (ca. 6.0 m in diameter) and very high tip speed (ca. 671 m/s) were employed. It was concluded that a single stage compressor was not feasible for compressing water vapor as refrigerant and that these factors combined yield extremely high capital cost and technically challenging compressor design and development. In order to achieve such a high performance, a two stage centrifugal compressor was evaluated and showed more favorable results. The investigation showed that a lower tip speed of around 490 m/s and efficiencies of 80% with large impeller diameters are technically possible for this task. However, in terms of total size and performance, it is identified that the most promising compressor technology is multi-stage axial compressor configuration consisting of between six and seven stages. When compared with centrifugal compressors, it is

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Nomenclature

C_p	specific heat capacity, J/g K
G_k	generation of turbulence kinetic energy, m^2/s^2
R	gas constant, J/mol K
u	velocity, m/s
γ	specific heat ratio
δ_{ij}	Kronecker delta
ε	energy dissipation rate, m^2/s^3
κ	turbulence kinetic energy, m^2/s^2
μ	laminar viscosity, m^2 s^{-1}
μ_t	turbulent viscosity, m^2 s^{-1}
ρ	density, kg/m^3
σ_k	turbulent Prandtl number for k
σ_ε	turbulent Prandtl number for ε

expensive and challenging to implement as many stages. Therefore, to reduce manufacturing cost and simplify setup process, it is imperative to have new technology.

A novel axial composite impeller manufacturing technology has been discussed previously [5,6] through this filament winding technology, cost effective light-weight composite impellers can be produced and tip speeds of more than 500 m/s can be achieved. Eyler [7] discussed several patterns which were able to be produced using this novel technology; also by utilizing these kinds of novel impellers, Demiss [2] claimed that if only several stages of these axial impellers provide good enough aerodynamic performance, energy saving around 30% will be realized using water vapor as refrigerant in a multi-stage counter rotating compressor system, which is illustrated in Fig. 2. CFD has been widely recognized as a powerful method for predicting the performance and understanding the fluid flow characteristics for compressors [8–12]. The purpose of the present study is to investigate the feasibility of the various novel axial impeller designs and once a specific design is selected, then further numerical simulations with more stringent convergent criteria would be carried out before actually building the compressor and testing its performance. For this purpose, a one stage compressor with three different impeller patterns and another three different ratios between shroud tip and hub radius were studied. Based on the simulation results, the flow characteristics for different designs are investigated and the optimized setting design is defined as well.

In the following sections, investigated impeller geometries are introduced at first where novel properties of impellers are

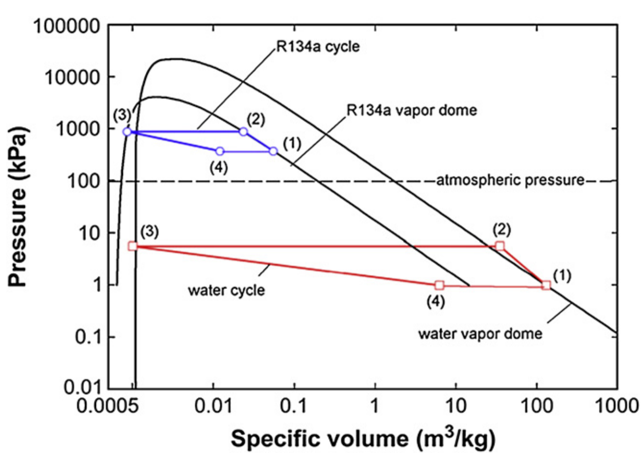

Fig. 1. Ideal cycle comparison between R718 (water) and R134a [2].

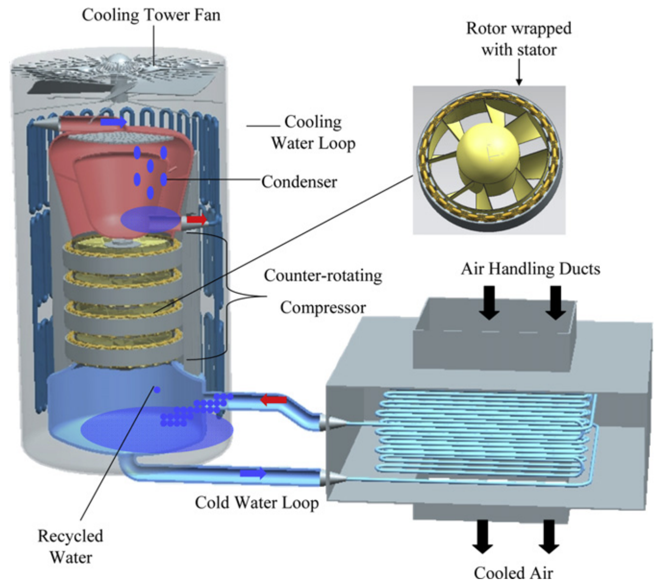

Fig. 2. Turbo chiller employing water refrigeration cycle.

explained. Then the results and discussion for six different settings are presented. Finally, conclusion is drawn and some design and optimization related suggestions are given.

2. Investigated impeller geometries

2.1. Impeller patterns

In the following, two different initial rotor patterns with the same blade angles at the shroud are compared aerodynamically through computational fluid dynamics. The same stator impeller is used for both patterns at the same specific hub/tip ratio. The present study investigates the feasibility of the various impeller designs accommodating different hub sizes. Further numerical simulations with more stringent convergent criteria shall be carried out before actually building the compressor and testing its performance and a better pattern can be selected.

Figs. 3 and 4 present two woven impeller patterns with the same shroud and hub diameters. These two impeller patterns can be manufactured in the same mandrel; thus they share the same blade angles at the shroud. The angle at the leading edge is set at 25° and 90° at the trailing edge relative to tangential direction. Since the wheel is weaved by crossing slots, different patterns mean different weaving routes for manufacturing. Therefore, blade angles at the shroud tip for different patterns are the same throughout, distribution of angles on the blade in the radial direction are different for different patterns. Considering that there are eight points on the shroud, and from a manufacturing view, when the second point of weaving is going to surpass two points, it is named B; and if it is going to surpass three points, it is named C. Interested readers can refer to detail manufacturing process and naming method in related publications [7]. Two patterns with name of 8B and 8C are going to be compared in this study. They were selected for ease of manufacture, structural stability and potential of aerodynamic performance. Since these impellers are located inside of specific chamber tube as illustrated in Fig. 5, the impeller's external diameter is fixed. The changing of hub size thus becomes an approach to improve the impeller's aerodynamic performance. Three radius ratios between hub and shroud tip such as 0.75, 0.54 and 0.43 are studied in this work. As for stators in these two sets of