is a phenomenon that occurs when the centrifugal compressor is operated at or near the minimum mass flow rate that the centrifugal compressor is capable of. It has been discovered that the operating range in which a centrifugal compressor can be operated without incurring choke or surge conditions can be widened by minimizing flow separation within the blade flow passage. By minimizing flow separation, the losses can be minimized and efficiency can be increased.

[0009] Thus, there is a need for centrifugal compressors that are optimized for use with new low-GWP refrigerants in chiller systems and other refrigeration applications in order to optimize the efficiency and operating range of the centrifugal compressor. In view of the state of the known technology, ~~an object~~embodiments of the present invention ~~is to~~ provide a centrifugal compressor having a non-ruled, fully nonlinear impeller that is optimized for use with low-GWP refrigerants in HVAC applications. By using computational fluid dynamics (CFD), the inventors have simulated the flow through a centrifugal compressor at design point mass flow rate as well as at higher mass flow rates (toward choke) and lower mass flow rates (toward surge). In this way, it has been discovered that a centrifugal compressor can be designed to have nearly zero flow separation at the design point mass flow rate and reduced flow separation at higher and lower mass flow rates. In particular, strategies for minimizing flow separation include adjusting the throat area of the centrifugal compressor (i.e., the narrowest area of the impeller inlet) and adjusting the blade curvature at locations where flow separation is found to occur. By using a non-ruled, fully nonlinear impeller blade, the blade curvature can be adjusted with a larger degree of freedom than a conventional 2D blade. Specifically, such features as a hub-side blade angle delta, a shroud-side blade angle delta, a hub-side wrap angle delta, and a shroud-side wrap angle delta can be adjusted. In this way, the shape of the impeller blades can be optimized for a particular low-GWP refrigerant used in a particular chiller system or other HVAC application having particular requirements regarding operating range and efficiency.

[0010] More specifically, in accordance with a first aspect of the present disclosure, a centrifugal compressor for use with a low global warming potential (GWP) refrigerant is provided which comprises a casing, a first impeller, and a motor. The casing has a first inlet portion and a first outlet portion. The first impeller is disposed between the first inlet portion and the first outlet portion. The first impeller is attached to a first end of a shaft that is rotatable about a rotation axis. The first impeller is equipped with first blades having a fully

nonlinear shape in a quasi-orthogonal cross-sectional view of the first impeller. A hub-side blade angle delta of each of the first blades from a hub portion of the first impeller to a mid-span position of the first blade varies along a streamwise direction such that the hub-side blade angle delta is largest at a first position closer to a leading edge of each of the first blades than to a trailing edge of each of the first blades. The motor is arranged inside the casing to rotate the shaft in order to rotate the first impeller. The casing is configured such that the low global warming potential (GWP) refrigerant enters the impeller from the first inlet portion along an axial direction of the first impeller and exits the first impeller to the first outlet portion in a radial direction of the first impeller.

[0011] In accordance with a second aspect of the present disclosure, a centrifugal compressor for use with a low global warming potential (GWP) refrigerant is provided which comprises a casing, a first impeller, and a motor. The casing has a first inlet portion and a first outlet portion. The first impeller is disposed between the first inlet portion and the first outlet portion. The first impeller is attached to a first end of a shaft that is rotatable about a rotation axis. The first impeller is equipped with first blades having a fully nonlinear shape in a quasi-orthogonal cross-sectional view. A hub-side wrap angle delta of each of the first blades from a hub portion of the first impeller to a mid-span position of each of the first blades varies along a streamwise direction such that the hub-side wrap angle delta is largest at a position closer to a leading edge of each of the first blades than to a trailing edge of each of the first blades. The motor is arranged inside the casing to rotate the shaft in order to rotate the first impeller. The casing is configured such that the low global warming potential (GWP) refrigerant enters the impeller from the first inlet portion along an axial direction of the first impeller and exits the first impeller to the first outlet portion in a radial direction of the first impeller.

[0012] In accordance with a third aspect of the present disclosure, a method of producing refrigeration is provided which comprises compressing a low global warming potential (GWP) refrigerant within a chiller system that includes a centrifugal compressor having an impeller attached to a shaft rotatable about a rotation axis. The impeller is equipped with blades

having a nonlinear shape in a quasi-orthogonal cross-sectional view. A hub-side blade angle delta of each of the blades from a hub portion of the impeller to a mid-span position of the blade varies along a streamwise direction such that the hub-side blade angle delta is largest at a position closer to a leading edge of the blades than to a trailing edge of the blades.

[0013] These and other ~~objects,~~ features, aspects and advantages of the present ~~invention~~disclosure will become apparent to those skilled in the art from the following detailed description, which, taken in conjunction with the annexed drawings, discloses preferred embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] Referring now to the attached drawings which form a part of this original disclosure:

[0015] Figure 1 is a schematic diagram illustrating a two stage chiller system (with an economizer) having a centrifugal compressor in accordance with an embodiment of the present invention;

[0016] Figure 2 is a perspective view of the centrifugal compressor of the chiller system illustrated in Figure 1 in accordance with a first embodiment featuring a closed type fully nonlinear impeller, with portions of the centrifugal compressor broken away and shown in cross-section for the purpose of illustration;

[0017] Figure 3 is a perspective view of the fully nonlinear impeller according to the embodiment with a portion cut away and shown in cross section;

[0018] Figure 4 illustrates two quasi-orthogonal cross sections of a blade of the fully nonlinear impeller;

[0019] Figure 5 illustrates two quasi-orthogonal cross sections of a conventional 2D blade of an impeller for a centrifugal compressor;

[0020] Figures 6A and 6B show cross sectional views of the fully nonlinear impeller according to the embodiment and the conventional 2D impeller, respectively, which include a rotational axis of the impeller;

~~WHAT IS CLAIMED IS:~~CLAIMS

1. A centrifugal compressor for use with a low global warming potential (GWP) refrigerant, the centrifugal compressor comprising:

a casing having a first inlet portion and a first outlet portion;

a first impeller disposed between the first inlet portion and the first outlet portion, the first impeller being attached to a first end of a shaft that is rotatable about a rotation axis, the first impeller being equipped with first blades having a fully nonlinear shape in a quasi-orthogonal cross-sectional view of the first impeller, a hub-side blade angle delta of each of the first blades from a hub portion of the first impeller to a mid-span position of the first blade varying along a streamwise direction such that the hub-side blade angle delta is largest at a first position closer to a leading edge of each of the first blades than to a trailing edge of each of the first blades;

a motor arranged inside the casing to rotate the shaft in order to rotate the first impeller,

the casing being configured such that the low global warming potential (GWP) refrigerant enters the impeller from the first inlet portion along an axial direction of the first impeller and exits the first impeller to the first outlet portion in a radial direction of the first impeller.

2. The centrifugal compressor according to claim 1, wherein

the position where the hub-side blade angle delta is largest is between 10% and 40% of a blade length of each of the first blades in the streamwise direction, where 0% corresponds to the leading edge and 100% corresponds to the trailing edge.

3. The centrifugal compressor according to claim 1 or 2, wherein

the hub-side blade angle delta is in a range of 10 to 30 degrees at the position where the hub-side blade angle delta is largest.

4. The centrifugal compressor according to any of claims 1-3, wherein

a hub-side wrap angle delta of each of the first blades from the hub portion to the mid-span position varies along ~~a~~ the streamwise direction such that the hub-side wrap angle

delta is largest at a second position closer to the leading edge than to the trailing edge.

5. The centrifugal compressor according to claim 4, wherein

the leading edge of each of the first blades has a nonlinear shape when the inlet side of the first impeller is viewed along a direction parallel to the rotational axis.

6. The centrifugal compressor according to any of claims 1-5, wherein

the first impeller is a closed type impeller including the hub portion and a shroud portion, the first blades being disposed between the hub portion and the shroud portion, and

a shroud-side blade angle delta of each of the first blades from the mid-span position to the shroud portion varies along the streamwise direction such that the shroud- side blade angle delta is largest at a third position closer to the leading edge of each of the first blades than to the trailing edge of each of the first blades.

7. The centrifugal compressor according to claim 6, wherein

the shroud-side blade angle delta has a second peak disposed closer to the trailing edge than to the leading edge, the second peak being smaller than the largest shroud-side blade angle delta.

8. The centrifugal compressor according to claim 6 or 7, wherein

the position where the shroud-side blade angle delta is largest is located between 10% and 40% of a blade length of each of the first blades in the streamwise direction, where 0% corresponds to the leading edge and 100% corresponds to the trailing edge.

9. The centrifugal compressor according to any of claims 6-8, wherein

the shroud-side blade angle delta is in a range of 6 to 14 degrees at the position where the shroud-side blade angle delta is largest.

10. The centrifugal compressor according to any of claims 6-9, wherein

a shroud-side wrap angle delta of each of the first blades from the mid-span position to

the shroud portion varies along ~~a~~ the streamwise direction such that the shroud-side wrap angle delta is largest at a fourth position closer to the leading edge than to the trailing edge.

11. The centrifugal compressor according to any of claims 1-10, wherein

a trailing edge of each of the first blades has a positive rake angle.

12. The centrifugal compressor according to any of claims 1-11, further comprising

a second impeller attached to the shaft,

the second impeller being disposed between a second inlet portion and a second outlet portion of the casing, the second impeller being equipped with second blades having a nonlinear shape in a quasi-orthogonal cross-sectional view of the second impeller, a hub-side blade angle delta of each of the second blades from a hub portion of the second impeller to a mid-span position of each of the second blades varying along a streamwise direction such that the hub-side blade angle delta of each of the second blades is largest at a position closer to a leading edge of each of the second blades than to a trailing edge of each of the second blades.

13. The centrifugal compressor according to claim 12, wherein

the first impeller and the second impeller are arranged back-to-back with the motor being disposed between the first impeller and the second impeller.

14. A centrifugal compressor for use with a low global warming potential (GWP) refrigerant, the centrifugal compressor comprising:

a casing having a first inlet portion and a first outlet portion; a first impeller disposed between the first inlet portion and the first outlet portion, the first impeller being attached to a first end of a shaft that is rotatable about a rotation axis, the first impeller being equipped with first blades having a fully nonlinear shape in a quasi-orthogonal cross-sectional view, a hub-side wrap angle delta of each of the first blades from a hub portion of the first impeller to a mid-span position of each of the first blades varying along a streamwise direction such that the hub-side wrap angle delta is largest at a position closer to a leading edge of each of the first blades than to a trailing edge of each of the first blades;

a motor arranged inside the casing to rotate the shaft in order to rotate the first impeller,

the casing being configured such that the low global warming potential (GWP) refrigerant enters the impeller from the first inlet portion along an axial direction of the first impeller and exits the first impeller to the first outlet portion in a radial direction of the first impeller.

15. The centrifugal compressor according to claim 14, wherein

the position where the hub-side wrap angle delta is largest is between 10% and 40% of a blade length of the first blade in the streamwise direction, where 0% corresponds to the leading edge and 100% corresponds to the trailing edge.

16. The centrifugal compressor according to claim 14 or 15, wherein

the hub-side wrap angle delta is in a range of 2 to 11 degrees at the position were the hub-side wrap angle delta is largest.

17. A method of producing refrigeration comprising:

compressing a low global warming potential (GWP) refrigerant within a chiller system that includes a centrifugal compressor having an impeller attached to a shaft rotatable about a rotation axis, the impeller being equipped with blades having a nonlinear shape in a quasi-orthogonal cross-sectional view, a hub-side blade angle delta of each of the blades from a hub portion of the impeller to a mid-span position of the blade varying along a streamwise direction such that the hub-side blade angle delta is largest at a position closer to a leading edge of the blades than to a trailing edge of the blades.

18. The method according to claim 17, wherein

the impeller is a closed type impeller including a hub portion and a shroud portion, the blades being disposed between the hub portion and the shroud portion.

19. The method according to claim 18, wherein

a curvature of the nonlinear shape in the quasi-orthogonal cross-sectional-view varies

along a length of the quasi-orthogonal cross-sectional view from the hub portion to the shroud portion.

20. A refrigeration circuit comprising:

the compressor according to any of claims 1-16;

a condenser;

an expansion valve;

an evaporator; and

piping connecting the compressor, the condenser, the expansion valve, and the evaporator to form a loop, the refrigeration circuit containing the low global warming potential (GWP) refrigerant.