Innovation, Sciences et Développement économique Canada
Office de la Propriété Intellectuelle du Canada

Innovation, Science and Economic Development Canada
Canadian Intellectual Property Office

CA 2897254 C 2018/05/01

(11)(21) **2 897 254**

(12) **BREVET CANADIEN
CANADIAN PATENT**

(13) **C**

(22) Date de dépôt/Filing Date: 2015/07/13
(41) Mise à la disp. pub./Open to Public Insp.: 2016/03/19
(45) Date de délivrance/Issue Date: 2018/05/01
(30) Priorité/Priority: 2014/09/19 (US14/491,778)

(51) Cl.Int./Int.Cl. *B64D 33/00* (2006.01), *B64D 29/00* (2006.01), *F02C 7/14* (2006.01), *F15D 1/02* (2006.01)

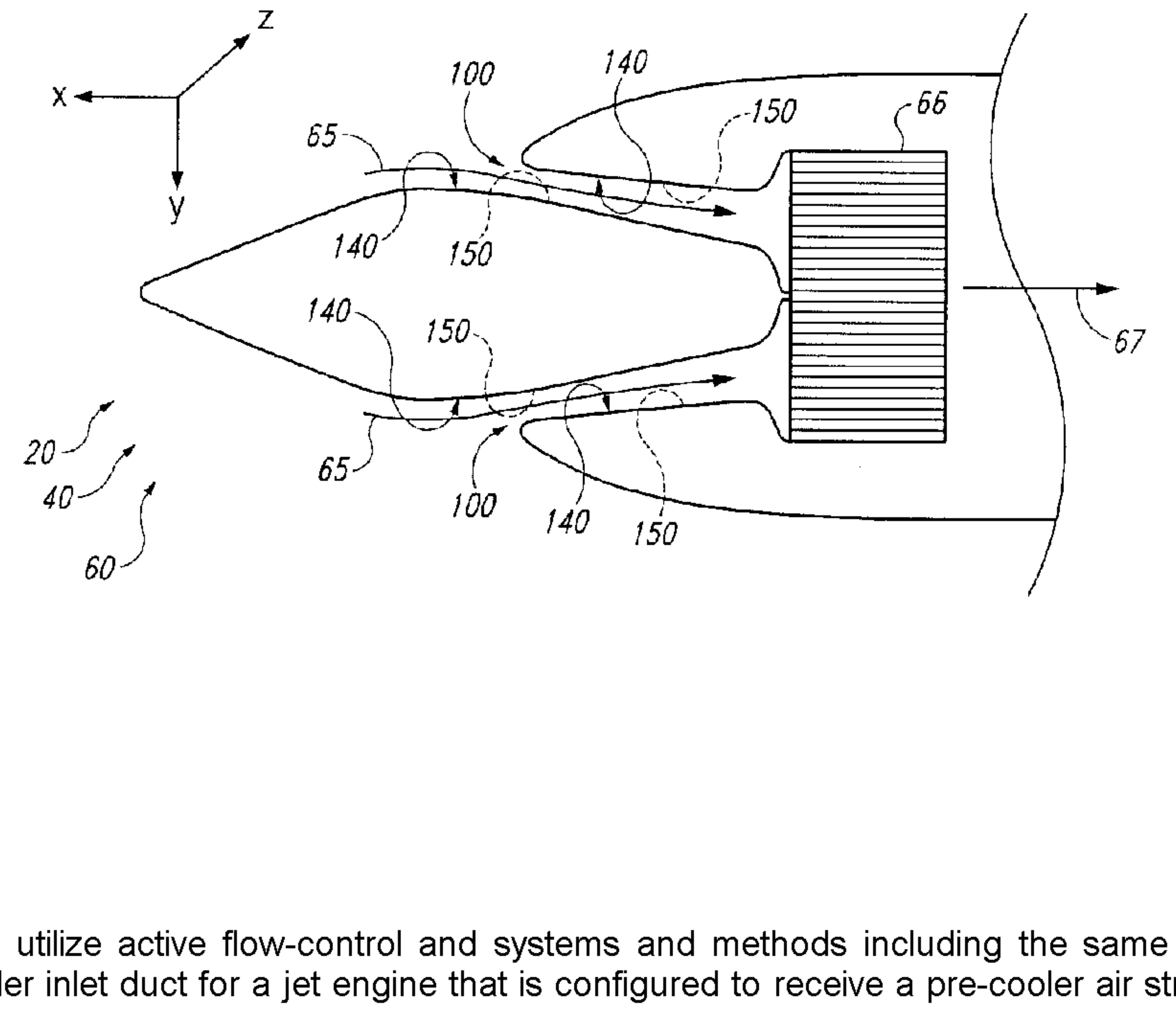
(72) Inventeurs/Inventors:
PACKARD, NATHAN O., US;
WILLIE, ROBERT H., US;
TRETOW, PAUL R., US

(73) Propriétaire/Owner:
THE BOEING COMPANY, US

(74) Agent: SMART & BIGGAR

(54) Titre : CONDUITS D'ENTREE DE PREREFROIDISSEUR QUI EMPLOIENT UNE COMMANDE DE DEBIT ACTIVE, ET SYSTEMES ET METHODES LES RENFERMANT

(54) Title: PRE-COOLER INLET DUCTS THAT UTILIZE ACTIVE FLOW-CONTROL AND SYSTEMS AND METHODS INCLUDING THE SAME



(57) Abrégé/Abstract:
Pre-cooler inlet ducts that utilize active flow-control and systems and methods including the same are disclosed herein. The systems include a pre-cooler inlet duct for a jet engine that is configured to receive a pre-cooler air stream and to direct the pre-cooler air stream into a heat exchanger. The pre-cooler inlet duct includes a flow- directing surface, which defines at least a portion of the pre-cooler inlet duct, and an active flow-control device. The active flow-control device is located to modify a boundary layer fluid flow within a boundary layer adjacent the flow-directing surface to resist separation of the boundary layer from the flow-directing surface when the pre-cooler air stream flows through the pre-cooler inlet duct. The methods include methods of resisting boundary layer separation in the pre-cooler inlet duct by flowing the pre-cooler air stream across the flow-directing surface and modifying the boundary layer with the active flow-control device.

ABSTRACT

Pre-cooler inlet ducts that utilize active flow-control and systems and methods including the same are disclosed herein. The systems include a pre-cooler inlet duct for a jet engine that is configured to receive a pre-cooler air stream and to direct the pre-cooler air stream into a heat exchanger. The pre-cooler inlet duct includes a flow-directing surface, which defines at least a portion of the pre-cooler inlet duct, and an active flow-control device. The active flow-control device is located to modify a boundary layer fluid flow within a boundary layer adjacent the flow-directing surface to resist separation of the boundary layer from the flow-directing surface when the pre-cooler air stream flows through the pre-cooler inlet duct. The methods include methods of resisting boundary layer separation in the pre-cooler inlet duct by flowing the pre-cooler air stream across the flow-directing surface and modifying the boundary layer with the active flow-control device.

PRE-COOLER INLET DUCTS THAT UTILIZE ACTIVE FLOW-CONTROL AND SYSTEMS AND METHODS INCLUDING THE SAME

FIELD

The present disclosure relates to pre-cooler inlet ducts for nacelles of jet engines, and more particularly to pre-cooler inlet ducts that utilize active flow-control to interact with, modify, and/or energize a boundary layer fluid flow within a boundary layer adjacent to the pre-cooler inlet duct, and to systems and methods including the pre-cooler inlet duct.

BACKGROUND

Nacelles for jet engines may include a pre-cooler inlet duct that may direct a pre-cooler air stream onto a heat exchanger assembly to cool engine bleed air prior to it being utilized by the jet engine and/or by another component of an aircraft that includes the jet engine. The pre-cooler inlet duct may be present within the nacelle and may be located to receive a portion of a compressed air stream that may be pressurized by a compressor of the jet engine.

Because the pre-cooler inlet is located within the nacelle, a size of the pre-cooler inlet may be restricted by a size of the nacelle. Conversely, a given size pre-cooler inlet may dictate a needed size for a nacelle that may contain the pre-cooler inlet. In addition, a desired flow rate of the pre-cooler air stream also may dictate a needed size for the pre-cooler inlet duct.

Under certain conditions, it may be desirable to increase the flow rate of the pre-cooler air stream without increasing the size of the pre-cooler inlet duct. Additionally or alternatively, it also may be desirable to decrease the size of the pre-cooler inlet duct, such as to permit the pre-cooler inlet duct to be placed within a smaller nacelle and/or to decrease a portion of the interior of the nacelle that is utilized by the pre-cooler inlet duct, without decreasing the flow rate of the pre-cooler air stream.

Historically, traditional aerodynamic principles have been utilized to design the size and/or shape of the pre-cooler inlet duct. However, these traditional aerodynamic principles may limit the size and/or shape of the pre-cooler inlet, thereby restricting increases in the flow rate of the pre-cooler air stream and/or decreases in the size of the nacelle. It is with such considerations in mind that examples according to the present disclosure are described in further detail below.

SUMMARY

Pre-cooler inlet ducts that utilize active flow-control and systems and methods including the same are disclosed herein. The systems include a pre-cooler inlet duct for a jet engine that is configured to receive a pre-cooler air stream and to direct the pre-cooler air stream into a heat exchanger. The pre-cooler inlet duct includes a flow-directing surface, which defines at least a portion of the pre-cooler inlet duct, and an active flow-control device. The active flow-control device is located to modify a boundary layer fluid flow within a boundary layer adjacent the flow-directing surface, such as to resist separation of the boundary layer from the flow-directing surface when the pre-cooler air stream flows through the pre-cooler inlet duct. The active flow-control device may modify the boundary layer in any suitable manner, such as by interacting with and/or energizing the boundary layer, to resist separation of the boundary layer from the flow-directing surface.

In some embodiments, a radius of curvature of the flow-directing surface is less than a radius of curvature of a conventional flow-directing surface that does not include the active flow-control device. In some embodiments, a length of the flow-directing surface is less than a length of the conventional flow-directing surface.

In some embodiments, the active flow-control device is configured to inject a flow-control fluid stream into the boundary layer through an injection orifice. In some embodiments, the injection orifice forms a portion of a sweeping jet. In some embodiments, the active flow-control device is configured to continuously inject the flow-control fluid stream. In some embodiments, the active flow-control device is configured to intermittently inject the flow-control fluid stream. In some embodiments, the active flow-control device is configured to inject a plurality of flow-control fluid streams. In some embodiments, the active flow-control device is configured to vary which of the plurality of flow-control fluid streams is being injected at a given point in time.

In some embodiments, the active flow-control device includes a vortex generator configured to generate a vortex within the boundary layer. In some embodiments, the active flow-control device includes a suction assembly configured to remove a suction stream from the boundary layer.

In some embodiments, the pre-cooler inlet duct forms a portion of a nacelle for a jet engine. In some embodiments, the nacelle forms a portion of an aircraft.

The methods include methods of resisting boundary layer separation in the pre-cooler inlet duct. The methods include flowing the pre-cooler air stream across the flow-directing surface to generate a boundary layer adjacent the flow-directing surface. The methods further include modifying the boundary layer with the active flow-control device to resist separation of the boundary layer from the flow-directing surface.

In one embodiment, there is provided a pre-cooler inlet duct for receiving and directing a pre-cooler air stream into a heat exchanger. The pre-cooler inlet duct includes a flow-directing surface that defines at least a portion of the pre-cooler inlet duct and an injection orifice in communication with the portion of the pre-cooler inlet duct. The flow-directing surface is shaped to direct the pre-cooler air stream into the heat exchanger. The pre-cooler inlet duct further includes an active flow-control device which injects, through the injection orifice, at an injection angle measured in a plane parallel to a surface normal direction of the flow-directing surface, a flow-control fluid stream into a boundary layer adjacent the flow-directing surface to modify a boundary layer fluid flow within the boundary layer and to resist separation of the boundary layer from the flow-directing surface when the pre-cooler air stream flows through the pre-cooler inlet duct. The injection orifice periodically varies the injection angle between an upper angle limit and a lower angle limit.

In another embodiment, there is provided a nacelle for a jet engine. The nacelle includes an inlet for receiving an air stream and a pre-cooling assembly including the pre-cooler inlet duct described above and/or any of its variants. The pre-cooler inlet duct is fluidly coupled to the inlet of the nacelle.

In another embodiment, there is provided a jet engine including the nacelle described above and/or any of its variants.

In another embodiment, there is provided a method of resisting boundary layer separation from a flow-directing surface of a pre-cooler inlet duct. The method involves flowing a pre-cooler air stream across the flow-directing surface and through the pre-cooler inlet duct. The flowing includes generating a boundary layer adjacent the flow-directing surface. The boundary layer includes a boundary layer fluid flow. The method further involves modifying the boundary layer fluid flow with an active flow-control device to resist separation of the boundary layer from the flow-directing surface by injecting a flow-control fluid stream through an injection orifice defined by the flow-directing surface, at an injection angle measured in a plane parallel to a surface normal direction of the flow-directing surface, such that the flow-control fluid stream is injected into the boundary layer. The method further involves periodically varying, by the injection orifice, the injection angle between an upper angle limit and a lower angle limit.

In another embodiment, there is provided a jet engine including a nacelle including an inlet for receiving an air stream, a compressor positioned within the nacelle and for receiving the air stream and pressurizing the air stream to generate a compressed air stream, a pre-cooler inlet duct positioned within the nacelle and for receiving a portion of the compressed air stream as a pre-cooler air stream, and a heat exchanger positioned within the nacelle and for receiving the pre-cooler air stream. The pre-cooler inlet duct is further for directing the pre-cooler air stream into the heat exchanger. The pre-cooler inlet duct includes: (i) a flow-directing surface that defines at least a portion of the pre-cooler inlet duct and is shaped to direct the pre-cooler air stream into the heat exchanger; and (ii) an active flow-control device

CA 2897254 2017-10-20

which injects a flow-control fluid stream into a boundary layer, through an injection orifice that is defined by the flow-directing surface, to modify the boundary layer fluid flow within a boundary layer adjacent the flow-directing surface to resist separation of the boundary layer from the flow-directing surface when the pre-cooler air stream flows through the pre-cooler inlet duct. The injection orifice injects the flow-control fluid stream at an injection angle, which is measured in a plane that is parallel to a surface normal direction of the flow-directing surface, that periodically varies between a lower angle limit and an upper angle limit.

In another embodiment, there is provided a method of resisting boundary layer separation from a flow-directing surface of a pre-cooler inlet duct of a jet engine. The method involves receiving an air stream with an inlet of a nacelle of the jet engine, compressing the air stream with a compressor of the jet engine to pressurize the air stream and generate a compressed air stream, and flowing a portion of the compressed air stream, as a pre-cooler air stream, across the flow-directing surface of the pre-cooler inlet duct and through the pre cooler inlet duct. The flowing includes generating a boundary layer adjacent the flow-directing surface. The boundary layer includes a boundary layer fluid flow. The method further involves modifying the boundary layer fluid flow with an active flow-control device to resist separation of the boundary layer from the flow-directing surface of the pre-cooler inlet duct. The modifying includes injecting a flow-control fluid stream into the boundary layer through an injection orifice that is defined by the flow-directing surface. The injection orifice injects the flow-control fluid stream at an injection angle, which is measured in a plane that is parallel to a surface normal direction of the flow-directing surface. The injecting includes periodically varying the injection angle between a lower angle limit and an upper angle limit.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. **1** is a schematic representation of examples of an aircraft that may include a jet engine that may include a pre-cooler inlet duct according to the present disclosure.

Fig. **2** is a schematic partially fragmentary side view illustrating examples of a jet engine that may include a pre-cooler inlet duct according to the present disclosure.

Fig. **3** is a schematic front view illustrating examples of a jet engine that may include a pre-cooler inlet duct according to the present disclosure.

Fig. **4** is a schematic cross-sectional view illustrating examples of a pre-cooler inlet duct according to the present disclosure.

Fig. **5** is a schematic cross-sectional view illustrating examples of a pre-cooler inlet duct according to the present disclosure.

Fig. **6** is a schematic cross-sectional view comparing a conventional flow-directing surface to a flow-directing surface according to the present disclosure.

Fig. **7** is a schematic cross-sectional view comparing two flow-directing surfaces according to the present disclosure.

Fig. **8** is a flowchart depicting methods, according to the present disclosure, of resisting boundary layer separation from a pre-cooler inlet duct.

DESCRIPTION

Figs. **1-8** provide illustrative, non-exclusive examples of pre-cooler inlet ducts **100** that include active flow-control devices **150** according to the present disclosure, of nacelles **54** for jet engines **40** that include pre-cooler inlet ducts **100**, of aircraft **20** that include jet engines **40**, and/or of methods of operating the same. Elements that serve a similar, or at least substantially similar, purpose are labeled with like numbers in each of Figs. **1-8**, and these elements may not be discussed in detail herein with reference to each of Figs. **1-8**. Similarly, all elements may not be labeled in each of Figs. **1-8**, but reference numerals associated therewith may be utilized herein for consistency. Elements, components, and/or features that are discussed herein with reference to one or more of Figs. **1-8** may be included in and/or utilized with any of Figs. **1-8** without departing from the scope of the present disclosure.

In general, elements that are likely to be included in a given (i.e., a particular) embodiment are illustrated in solid lines, while elements that are optional to a given embodiment are illustrated in dashed lines. However, elements that are shown in solid lines are not essential to all embodiments, and an element shown in solid lines may be omitted from a given embodiment without departing from the scope of the present disclosure.

Fig. **1** is a schematic representation of an illustrative, non-exclusive example of an aircraft **20** that may include a jet engine **40** that includes a pre-cooling assembly **60** with a pre-cooler inlet duct **100** according to the present disclosure, while Figs. **2-3** are more detailed but still illustrative, non-exclusive examples of a jet engine **40** that includes a pre-cooling assembly **60** with a pre-cooler inlet duct **100** according to the present disclosure. More specifically, Fig. **2** is a schematic partially fragmentary side view of jet engines **40**, while Fig. **3** is a schematic front view of jet engines **40**.

As illustrated in Fig. **1**, aircraft **20** includes an airframe **30**, which is operatively attached to and/or configured to support one or more jet engines **40**. As further illustrated in Fig. **1**, jet engines **40** may include a nacelle **54** that may be sized and/or shaped to define, contain, and/or house a variety of components of jet engine **40**. As examples, jet engines **40** may include an inlet **42**, which is configured to receive an air stream **43**, and a compressor **44**, which is configured to compress (or increase a pressure of) air stream **43** to generate a compressed air stream **45**. Jet engines **40** also may include a burner **46**, which is configured to combust a fuel stream with a portion **53** of compressed air stream **45** to generate a combustion stream, and a turbine **48**, which is configured to be powered by the combustion stream and to power compressor **44**.

As illustrated in Figs. **1-2**, jet engines **40** further may include a nozzle **50**, which is configured to permit the combustion stream to be expelled from (or to exit) jet engine **40**. As illustrated most clearly in Fig. **2**, jet engines **40** may define a central duct **52**, which is configured to receive portion **53** of compressed air stream **45** from compressor **44**, and pre-cooler inlet duct **100**, which is configured to receive another portion of compressed air stream **45**, which is referred to herein as a pre-cooler air stream **65**. Pre-cooler inlet duct **100** may form a portion of pre-cooling assembly **60** and may provide and/or direct pre-cooler air stream **65** to and/or toward a heat exchanger **66**. Heat exchanger **66** may be configured to exchange thermal energy with pre-cooler air stream **65** to generate a heat-exchanged air stream **67**. Heat-exchanged air stream **67** may be provided to another component of jet engine **40** and/or of aircraft **20**.

As discussed in more detail herein, and when pre-cooler air stream **65** is flowing through pre-cooler inlet duct **100**, an active flow-control device **150** may be configured, utilized, and/or operated to resist separation of a boundary layer **80**, which includes a boundary layer fluid flow **82**, from a flow-directing surface **140** of pre-cooler inlet duct **100**. As an illustrative, non-exclusive example, active flow-control device **150** may be configured to modify boundary layer fluid flow **82**, thereby changing one or more characteristics of boundary layer fluid flow **82** and permitting boundary layer fluid flow **82** to flow across flow-directing surface **140** without separation therefrom.

In general, pre-cooling assemblies **60** and/or pre-cooler inlet ducts **100** according to the present disclosure that include active flow-control device **150** may be configured to maintain and/or retain boundary layer **80** attached to flow-directing surface **140** over a wide range of average pre-cooler air stream speeds of pre-cooler air stream **65**. As illustrative, non-exclusive examples, pre-cooling assemblies **60** and/or pre-cooler inlet ducts **100** according to the present disclosure may maintain boundary layer **80** attached to pre-cooler inlet duct **100** when the average pre-cooler air stream speed is at least **50** meters/second (m/s), at least **75** m/s, at least **100** m/s, at least **125** m/s, at least **150** m/s, at least **175** m/s, at least **200** m/s, at least **225** m/s, at least **250** m/s, at least **275** m/s, and/or at least **300** m/s.

Additionally or alternatively, pre-cooling assemblies **60** also may maintain boundary layer **80** attached to flow-directing surface **140** when the average pre-cooler air stream speed is less than **350** m/s, less than **325** m/s, less than **300** m/s, less than **275** m/s, less than **250** m/s, less than **225** m/s, and/or less than **200** m/s.

Active flow-control device **150** may include and/or utilize any suitable active flow-control technology. As an illustrative, non-exclusive example, and as discussed in more detail herein, active flow-control device **150** may be configured to inject a flow-control fluid stream into boundary layer **80**. As another illustrative, non-exclusive example, active flow-control device **150** may include a vortex generator that is configured to generate a vortex within boundary layer **80**. As yet another illustrative, non-exclusive example, active flow-control device **150** may be configured to remove a suction stream from boundary layer **80**.

It is within the scope of the present disclosure that active flow-control device **150** may supply the flow-control fluid stream, may generate the vortex, and/or may remove the suction stream in any suitable manner and/or utilizing any suitable equipment. As illustrative, non-exclusive examples, active flow-control device **150** may include one or more of a piezoelectric actuator, a shape memory alloy actuator, a diaphragm, a pump, a compressor, and/or a fan.

As illustrated in Fig. **3**, pre-cooling assembly **60** and pre-cooler inlet duct **100** thereof may be located within an internal volume **56** of nacelle **54**. Thus, a size, shape, and/or volume of pre-cooling assembly **60** and/or of pre-cooler inlet duct **100** may be constrained by a target, desired, and/or specified size of nacelle **54** and/or by a size and/or geometry of the other components that may be present within internal volume **56**.

As discussed, it may be desirable to increase a flow rate of pre-cooler air stream **65** (as illustrated in Fig. **2**) into pre-cooler inlet duct **100** without increasing the size of nacelle **54**, and pre-cooling assemblies **60** with bifurcated pre-cooler inlets have been utilized to provide for this increase in flow rate of pre-cooler air stream **65**. Such a bifurcated pre-cooler inlet includes two pre-cooler inlet ducts **100**. One of these pre-cooler inlet ducts **100** is illustrated in solid lines in Fig. **3**, while the other pre-cooler inlet duct **100** is illustrated in dashed lines to indicate that the second pre-cooler inlet duct may be optional. While bifurcated pre-cooler inlets may provide for a measurable increase in the flow rate of pre-cooler air stream **65**, it may be desirable to further increase the flow rate of pre-cooler air stream **65** and/or to utilize pre-cooling assemblies that include only a single pre-cooler inlet duct. This may be accomplished by locating one or more active flow-control devices **150** on one or more flow-directing surfaces **140** of pre-cooling assembly **60**, and is discussed in more detail herein.

Figs. **4-5** provide schematic cross-sectional views of illustrative, non-exclusive examples of pre-cooler inlet ducts **100** that may be utilized in pre-cooling assemblies **60** according to the present disclosure. The schematic cross-sectional views of Figs. **4-5** may be taken along line A-A of Fig. **3**.

In Figs. **4-5**, pre-cooling assemblies **60** include one or more pre-cooler inlet ducts **100**. Pre-cooler inlet duct **100** may be at least partially defined by one or more flow-directing surfaces **140** and may be configured to direct a pre-cooler air stream **65** toward and/or into contact with a heat exchanger **66**. Heat exchanger **66** receives pre-cooler air stream **65** and produces heat-exchanged air stream **67** therefrom. In Fig. **4**, pre-cooling assembly **60** includes a bifurcated pre-cooler inlet that includes two pre-cooler inlet ducts **100**. In contrast, pre-cooling assembly **60** of Fig. **5** includes a single pre-cooler inlet duct **100**.

In Figs. **4-5**, one or more flow-directing surface **140** may include and/or utilize one or more active flow-control devices **150**. Active flow-control devices **150** may be configured to resist separation of a boundary layer fluid flow **82** of a boundary layer **80** from respective flow-directing surfaces **140**, as illustrated in Fig. **6** and discussed in more detail herein. As also discussed in more detail herein, the presence of active flow-control devices **150** may permit a decrease in one or more dimensions of pre-cooler inlet ducts **100** and/or of pre-cooling assembly **60** and/or may permit pre-cooling assemblies **60** to utilize a single pre-cooler inlet duct **100** (as illustrated in Fig. **5**) as opposed to a bifurcated pre-cooler inlet that includes two pre-cooler inlet ducts **100** (as illustrated in Fig. **4**) while maintaining a target, or desired, flow rate for pre-cooler air stream **65** and/or for heat-exchanged air stream **67**. In this manner, a size of a pre-cooler inlet duct **10** and/or pre-cooling assembly **60** may be reduced without reduction in performance of the pre-cooling assembly **60**.

Active flow-control devices **150** are illustrated in dashed lines in Figs. **4-5** to indicate that active flow-control devices **150** may be located and/or present on any suitable flow-directing surface **140** of pre-cooler inlet ducts **100** according to the present disclosure. As an example, active flow-control devices **150** may be located on multiple (i.e., two or more) flow-directing surfaces **140** that define a given pre-cooler inlet duct **100** (e.g. opposing surfaces **140** of upper and/or lower pre-cooler inlet duct **100** in Fig. **4** or opposing surfaces **140** of the single pre-cooler inlet duct **100** in Fig. **5**). As another example, active flow-control devices **150** may be located on one flow-directing surface **140** that defines the given pre-cooler inlet duct **100** but not on another flow-directing surface **140** that defines the given pre-cooler inlet duct **100**. As yet another example, flow-control devices **150** may be located on portion(s) of flow-directing surfaces **140** where a large change in direction of boundary layer fluid flow **82** (illustrated in Fig. **6**) is present. This may include portion(s) of flow-directing surfaces **140** that have and/or define a (relatively) smaller radius of curvature **104**, as discussed herein with reference to Figs. **6**-**7**.

Fig. **6** is a schematic cross-sectional view of a portion of a pre-cooling assembly **60** including a pre-cooler inlet duct **100** that is at least partially defined by a flow-directing surface **140** according to the present disclosure. As illustrated in Fig. **6**, flow-directing surface **140** includes one or more active flow-control devices **150** according to the present disclosure. As discussed, active flow-control devices **150** may be configured to interact with, modify, and/or energize a boundary layer fluid flow **82** that is present within a boundary layer **80** of a pre-cooler air stream **65** that is flowing past flow-directing surface **140** to resist separation of boundary layer **80** from flow-directing surface **140**. This may be accomplished in any suitable manner.

As an illustrative, non-exclusive example, active flow-control device **150** may be configured to inject one or more flow-control fluid streams **152** into boundary layer **80** through an injection orifice **154** that may be defined by, within, and/or on flow-directing surface **140**. Flow-control fluid stream **152** may be injected into boundary layer **80** in any suitable manner. As an illustrative, non-exclusive example, flow-control fluid stream **152** may be injected at a flow speed, or average flow speed, of at least **100** meters/second (m/s), at least **125** m/s, at least **150** m/s, at least **175** m/s, at least **200** m/s, at least **225** m/s, at least **250** m/s, at least **275** m/s, at least **300** m/s, at least **350** m/s, at least **400** m/s, at least **450** m/s, or at least **500** m/s. As another illustrative, non-exclusive example, flow-control fluid stream **152** may be injected at a flow speed, or average flow speed, of less than **700** m/s, less than **650** m/s, less than **600** m/s, less than **550** m/s, less than **500** m/s, less than **450** m/s, less than **400** m/s, less than **350** m/s, less than **325** m/s, less than **300** m/s, less than **275** m/s, less than **250** m/s, less than **225** m/s, and/or less than **200** m/s. As yet another illustrative, non-exclusive example, flow-control fluid stream **152** may be injected through injection orifice **154** such that a pressure differential across the injection orifice is at least **1** kilopascal (kPa), at least **5** kPa, at least **10** kPa, at least **15** kPa, at least **20** kPa, at least **25** kPa, at least **30** kPa, at least **35** kPa, at least **40** kPa, at least **50** kPa, at least **75** kPa, at least **100** kPa, at least **150** kPa, at least **200** kPa, at least **300** kPa, at least **400** kPa, at least **500** kPa, at least **600** kPa, and/or at least **700** kPa.

It is within the scope of the present disclosure that active flow-control device **150** may be configured to continuously, or at least substantially continuously, inject flow-control fluid stream **152** into boundary layer **80** when pre-cooler air stream **65** is flowing past flow-directing surface **140**. Additionally or alternatively, it is also within the scope of the present disclosure that active flow-control device **150** may be configured to intermittently, selectively, and/or periodically inject flow-control fluid stream **152** into boundary layer **80** when pre-cooler air stream **65** is flowing past flow-directing surface **140**.

Flow-control fluid stream **152** may be injected into boundary layer **80** at any suitable location. As an illustrative, non-exclusive example, active flow-control device **150** may be configured to inject a plurality of flow-control fluid streams **152** into boundary layer **80**. This may include injecting the plurality of flow-control fluid streams in a spaced-apart manner around a curvature, or radius of curvature, **104** of flow-directing surface **140**, as illustrated in Fig. **6**. Additionally or alternatively, this also may include injecting the plurality of flow-control fluid streams in a spaced-apart manner along a length of flow-directing surface **140** (i.e., in a spaced-apart manner along the Z-axis of Fig. **6**).

As yet another illustrative, non-exclusive example, flow-control fluid stream **152** may be injected behind, downstream of, and/or on a lee side of a step **130** on a surface of flow-directing surface **140**. Step **130** may include and/or be any suitable discontinuity and/or change in profile of flow-directing surface **140** and also may be referred to herein as a discontinuity **130**.

Flow-control fluid stream **152** may be generated in any suitable manner. As an illustrative, non-exclusive example, flow-control fluid stream **152** may include and/or be a portion of compressed air stream **45** that is generated by jet engine **40** and/or by compressor **44** thereof (as illustrated in Figs. **1-2**). Additionally or alternatively, flow-control fluid stream **152** may include and/or be a synthetic jet that is generated by a synthetic jet generator **158**.

As another illustrative, non-exclusive example, active flow-control device **150** may include a suction assembly **160** that is configured to withdraw a suction stream **161** from boundary layer **80**. As yet another illustrative, non-exclusive example, active flow-control device **150** may include a vortex generator **156** that is configured to generate a vortex **157** within boundary layer **80**. Vortex generator **156** may include any suitable active and/or passive vortex generator **156** that is configured to generate vortex **157** in any suitable manner. As illustrative, non-exclusive examples, vortex generator **156** may include a physical obstruction and/or a vortex generator jet actuator.

When active flow-control device **150** injects flow-control fluid stream **152** into boundary layer **80**, flow-control fluid stream **152** may be injected with any suitable orientation and/or at any suitable angle, or injection angle. As an illustrative, non-exclusive example, flow-control fluid stream **152** may be injected into boundary layer **80** at a first injection angle **170**. First injection angle **170** may be measured in a first plane that is parallel to a surface normal direction **168** of flow-directing surface **140**, and it is within the scope of the present disclosure that first injection angle **170** may include and/or be any suitable angle. The first plane also may be perpendicular to a length of flow-directing surface **140** (i.e., the Z-direction in Fig. **6**).

In addition, flow-control fluid stream **152** also may be injected into boundary layer **80** at a second injection angle **174**. Second injection angle **174** may be measured in a second plane that is parallel to surface normal direction **168** and perpendicular to the first plane, and it is within the scope of the present disclosure that second injection angle **174** may include any suitable angle. The second plane also may be parallel to the length of flow-directing surface **140**.

Illustrative, non-exclusive examples of first injection angle **170** and/or second injection angle **174** include angles of at least **0** degrees, at least **5** degrees, at least **10** degrees, at least **15** degrees, at least **20** degrees, at least **30** degrees, at least **40** degrees, at least **50** degrees, at least **60** degrees, at least **70** degrees, at least **80** degrees, at least **90** degrees, at least **100** degrees, at least **110** degrees, at least **120** degrees, at least **130** degrees, at least **140** degrees, at least **150** degrees, at least **160** degrees, and/or at least **170** degrees. As additional illustrative, non-exclusive examples, first injection angle **170** and/or second injection angle **174** may include angles of less than **180** degrees, less than **170** degrees, less than **160** degrees, less than **150** degrees, less than **140** degrees, less than **130** degrees, less than **120** degrees, less than **110** degrees, less than **100** degrees, less than **90** degrees, less than **80** degrees, less than **70** degrees, less than **60** degrees, less than **50** degrees, less than **40** degrees, less than **30** degrees, less than **20** degrees, less than **15** degrees, less than **10** degrees, and/or less than **5** degrees.

It is within the scope of the present disclosure that first injection angle **170** and/or second injection angle **174** may be a variable angle that varies between any of the above-listed lower limits and any of the above-listed upper limits. Under these conditions, flow-control fluid stream **152** may be generated by a sweeping jet that systematically and/or periodically varies the first injection angle and/or the second injection angle.

The plurality of active flow-control devices may include any suitable number of active flow-control devices. As illustrative, non-exclusive examples, flow-directing surface **140** may include at least **4**, at least **8**, at least **9**, at least **12**, at least **18**, at least **24**, at least **36**, at least **72**, at least **90**, at least **120**, at least **180**, at least **270**, and/or at least **360** active flow-control devices **150** and/or injection orifices **154**, or may be configured to inject a corresponding number of flow-control fluid streams **152**. As additional illustrative, non-exclusive examples, flow-directing surface **140** also may include fewer than **36**, fewer than **72**, fewer than **90**, fewer than **120**, fewer than **180**, fewer than **270**, fewer than **360**, and/or fewer than **720** active flow-control devices **150** and/or injection orifices **154**, or may be configured to inject a corresponding number of flow-control fluid streams **152**.

When flow-directing surface **140** includes the plurality of active flow-control devices **150** and/or is configured to inject the plurality of flow-control fluid streams **152**, the plurality of flow-control fluid streams **152** may be injected in any suitable manner. As an illustrative, non-exclusive example, each of the plurality of flow-control fluid streams may be injected continuously when pre-cooler air stream **65** is flowing past flow-directing surface **140** and/or thorough pre-cooler inlet duct **100**. As another illustrative, non-exclusive example, one or more of the flow-control fluid streams **152** may be injected intermittently. This may include (systematically) varying which of the plurality of flow-control fluid streams **152** is being injected at a given point in time.

When active flow-control device **150** is configured to inject the plurality of flow-control fluid streams **152**, the plurality of flow-control fluid streams may be injected through the plurality of injection orifices **154**, which may be defined by flow-directing surface **140**. It is within the scope of the present disclosure that the plurality of injection orifices **154** may include any suitable cross-sectional shape, including circular, elongate, slotted, square, arcuate, and/or rectangular cross-sectional shapes, and that at least a portion of the plurality of injection orifices **154** may have a different cross-sectional shape and/or size relative to a remainder of the plurality of injection orifices **154**. It is also within the scope of the present disclosure that active flow-control device **150** may include a continuous, or at least substantially continuous, slot that may be configured to inject one or more flow-control fluid streams along and/or across flow-directing surface **140**.

Fig. **7** is a schematic cross-sectional view comparing a conventional pre-cooler inlet duct **110** (illustrated in dashed lines) to a pre-cooler inlet duct **100** according to the present disclosure that includes an active flow-control device **150** (illustrated in solid lines). Pre-cooler inlet ducts **100** according to the present disclosure that include active flow-control devices **150** may provide improved performance over conventional pre-cooler inlet ducts **110** that do not include active flow-control devices **150**.

As an illustrative, non-exclusive example, a boundary layer fluid flow **82** within boundary layer **80** that is adjacent a flow-directing surface **140** of pre-cooler inlet duct **100** may define the performance of pre-cooler inlet duct **100**. Similarly, a boundary layer fluid flow within a boundary layer that is attached to a conventional flow-directing surface **180** of conventional pre-cooler inlet duct **110** also may define the performance of conventional pre-cooler inlet duct **110**. The presence of active flow-control devices **150** in pre-cooler inlet duct **100** according to the present disclosure, may permit pre-cooler inlet duct **100** to have a comparable, or even greater, performance despite having a shorter length **102** than a conventional length **112** of conventional pre-cooler inlet duct **110** and/or despite defining a smaller radius of curvature **104** when compared to a conventional radius of curvature **114** of conventional pre-cooler inlet duct **110**. The lengths may be defined relative to a starting point **101** at which a profile of flow-directing surface **140** and/or conventional flow-directing surface **180** changes in order to direct and/or bend boundary layer fluid flow **82**. Similarly, the radii of curvature may approximate and/or be a radius of curvature traveled by at least a portion of boundary layer fluid flow **82** as boundary layer fluid flow **82** flows around flow-directing surface **140** and/or conventional flow-directing surface **180**, respectively.

As illustrative, non-exclusive examples, length **102** may be less than **90**%, less than **80**%, less than **70**%, less than **60**%, less than **50**%, less than **40**%, less than **30**%, and/or less than **20**% of conventional length **112**. Additionally or alternatively, radius of curvature **104** may be less than **90**%, less than **80**%, less than **70**%, less than **60**%, less than **50**%, less than **40**%, less than **30**%, and/or less than **20**% of conventional radius of curvature **114**.

Decreasing length **102** and/or radius of curvature **104** relative to conventional length **112** and/or conventional radius of curvature **114** may provide performance benefits within jet engines **40** that include pre-cooling assemblies **60** and/or pre-cooler inlet ducts **100** according to the present disclosure. As an illustrative, non-exclusive example, decreasing length **102** and/or radius of curvature **104** may permit jet engines **40** according to the present disclosure to exhibit less weight and/or a smaller overall outer size when compared to comparable conventional jet engines due to the smaller length **102** and/or radius of curvature **104** of pre-cooler inlet duct **100**. This may decrease nacelle friction loss with jet engines **40**, increasing fuel economy. Additionally or alternatively, this also may provide for increased flexibility regarding location(s) where jet engines **40** may be mounted on aircraft **20**.

Fig. **8** is a flowchart depicting methods **200**, according to the present disclosure, of resisting boundary layer separation from a pre-cooler inlet duct. Methods **200** include flowing a pre-cooler air stream through a pre-cooler inlet duct at **210** and modifying a boundary layer with an active flow-control device at **220**.

Flowing the pre-cooler air stream through the pre-cooler inlet duct at **210** may include flowing across a flow-directing surface of the pre-cooler inlet duct and through the pre-cooler inlet duct. The flowing at **210** may include generating the boundary layer, which may include a boundary layer fluid flow, adjacent the flow-directing surface.

The flow-directing surface may define a radius of curvature and/or a length, and the flowing at **210** may include flowing the boundary layer (or the boundary layer fluid flow) along the radius of curvature and/or along the length. As discussed, the boundary layer fluid flow may define a threshold performance, and the radius of curvature may be less than a conventional radius of curvature of a conventional flow-directing surface that produces a comparable threshold performance but that does not utilize the modifying at **220**. Additionally or alternatively, the length may be less than a conventional length of the conventional flow-directing surface that produces the comparable threshold performance but that does not utilize the modifying at **220**. Examples of relationships between the radius of curvature and the conventional radius of curvature and/or between the length and the conventional length are disclosed herein.

Modifying the boundary layer at **220** may include modifying to resist separation of the boundary layer from the flow-directing surface of the pre-cooler inlet duct. This may include modifying any suitable characteristic, or flow characteristic, of the boundary layer and/or of the boundary layer fluid flow to decrease a potential for separation of the boundary layer from the flow-directing surface, such as under expected and/or nominal operating conditions of a jet engine that includes the pre-cooler inlet duct. As an illustrative, non-exclusive example, the modifying at **220** may include modifying to resist separation of the boundary layer from the flow-directing surface when an average flow speed of the pre-cooler air stream is at least **100** meters/second (m/s), at least **125** m/s, at least **150** m/s, at least **175** m/s, at least **200** m/s, at least **225** m/s, at least **250** m/s, at least **275** m/s, and/or at least **300** m/s. Additionally or alternatively, the modifying also may include modifying to resist separation of the boundary layer from the flow-directing surface when the average speed of the pre-cooler air stream is less than **350** m/s, less than **325** m/s, less than **300** m/s, less than **275** m/s, less than **250** m/s, less than **225** m/s, and/or less than **200** m/s.

The modifying at **220** may be accomplished in any suitable manner. As illustrative, non-exclusive examples, the modifying at **220** may include injecting a flow-control fluid stream into the boundary layer at **222**, generating a vortex within the boundary layer at **224**, and/or removing a suction stream from the boundary layer at **226**.

Injecting the flow-control fluid stream into the boundary layer at **222** may include injecting the flow-control fluid stream through an injection orifice that is defined by, within, and/or along the flow-directing surface. The injecting at **222** may include injecting at any suitable flow speed of the flow-control fluid stream, illustrative, non-exclusive examples of which are disclosed herein. Additionally or alternatively, the injecting at **222** also may include injecting such that any suitable pressure differential, illustrative, non-exclusive examples of which are disclosed herein, is developed across the injection orifice.

The injecting at **222** may include continuously, or at least substantially continuously, injecting the flow-control fluid stream during the flowing at **210**. Alternatively, the injecting at **222** also may include intermittently injecting the flow-control fluid stream during the flowing at **210**.

It is within the scope of the present disclosure that the injecting at **222** may include injecting at a first injection angle and/or injecting at a second injection angle. Illustrative, non-exclusive examples of the first injection angle and the second injection angle are disclosed herein.

The flow-control fluid stream may be generated in any suitable manner. As an illustrative, non-exclusive example, the injecting at **222** may include directing a compressed air stream through the injection orifice. The compressed air stream may be generated in any suitable manner, such as by the jet engine and/or via any suitable pump and/or compressor. As another illustrative, non-exclusive example, the injecting at **222** may include generating the flow-control fluid stream with a synthetic jet generator.

The injecting at **222** may include injecting a single flow-control fluid stream or a plurality of flow-control fluid streams. When the injecting at **222** includes injecting the plurality of flow-control fluid streams, the injecting at **222** further may include (systematically and/or periodically) varying which of the plurality of flow-control fluid streams is being injected into the boundary layer at a given point in time. Additionally or alternatively, and as discussed, the plurality of flow-control fluid streams may be injected in a spaced-apart manner across the flow-directing surface. Illustrative, non-exclusive examples of a spacing among the plurality of flow-control fluid streams and/or of a number of flow-control fluid streams (and/or corresponding injection orifices) in the plurality of flow-control fluid streams are disclosed herein.

Generating the vortex within the boundary layer at **224** may include generating the vortex in any suitable manner. As an illustrative, non-exclusive example, the generating at **224** may include generating with a vortex generator.

Removing the suction stream from the boundary layer at **226** may include removing the suction fluid stream from the boundary layer in any suitable manner. As an illustrative, non-exclusive example, the removing at **226** may include generating a vacuum within a suction assembly to remove the suction stream from the boundary layer.

Illustrative, non-exclusive examples of inventive subject matter according to the present disclosure are described in the following enumerated paragraphs:

In accordance with one embodiment, there is provided a pre-cooler inlet duct for a jet engine, wherein the pre-cooler inlet duct is configured to receive a pre-cooler air stream from a compressed air stream that is pressurized by a compressor of a jet engine and to direct the pre-cooler air stream into a heat exchanger. The pre-cooler inlet duct includes a flow-directing surface that defines at least a portion of the pre-cooler inlet duct and is shaped to direct the pre-cooler air stream into the heat exchanger. The pre-cooler inlet duct also includes an active flow-control device located to modify a boundary layer fluid flow within a boundary layer adjacent the flow-directing surface to resist separation of the boundary layer from the flow-directing surface when the pre-cooler air stream flows through the pre-cooler inlet duct.

The boundary layer fluid flow may define a threshold performance, and a radius of curvature of the flow-directing surface may be less than a conventional radius of curvature of a conventional flow-directing surface of a conventional pre-cooler inlet duct that produces a comparable threshold performance but that does not include the active flow control device.

The radius of curvature of the flow-directing surface may be less than **90**%, less than **80**%, less than **70**%, less than **60**%, less than **50**%, or less than **40**% of the conventional radius of curvature of the conventional flow-directing surface.

The boundary layer may define a/the threshold performance, and a length of the flow-directing surface may be less than a conventional length of a/the conventional flow-directing surface that produces a/the comparable threshold performance but that does not include the active flow-control device.

The length of the flow-directing surface may be less than **90**% less than **80**%, less than **70**%, less than **60**%, less than **50**%, or less than **40**% of the conventional length of the conventional flow-directing surface.

The pre-cooler inlet duct may include the boundary layer.

The pre-cooler inlet duct may include the boundary layer fluid flow.

The pre-cooler inlet duct may include the pre-cooler air stream.

The active flow-control device may be configured to resist separation of the boundary layer from the flow-directing surface when an average pre-cooler air stream flow speed through the pre-cooler inlet duct is at least one of: (i) at least **100** meters/second (m/s), at least **125** m/s, at least **150** m/s, at least **175** m/s, at least **200** m/s, at least **225** m/s, at least **250** m/s, at least **275** m/s, or at least **300** m/s, and (ii) less than **350** m/s, less than **325** m/s, less than **300** m/s, less than **275** m/s, less than **250** m/s, less than **225** m/s, or less than **200** m/s.

The active flow-control device may be configured to inject a flow-control fluid stream into the boundary layer through an injection orifice that is defined by the flow-directing surface.

The injection orifice may form a portion of a sweeping jet.

The pre-cooler inlet duct may include the flow-control fluid stream.

A flow speed of the flow-control fluid stream through the injection orifice may be at least one of: (i) at least **100** meters/second (m/s), at least **125** m/s, at least **150** m/s, at least **175** m/s, at least **200** m/s, at least **225** m/s, at least **250** m/s, at least **275** m/s, at least **300** m/s, at least **350** m/s, at least **400** m/s, at least **450** m/s, or at least **500** m/s, and (ii) less than **700** m/s, less than **650** m/s, less than

600 m/s, less than 550 m/s, less than 500 m/s, less than 450 m/s, less than 400 m/s, less than 350 m/s, less than 325 m/s, less than 300 m/s, less than 275 m/s, less than 250 m/s, less than 225 m/s, or less than 200 m/s.

A pressure differential of the flow-control fluid stream across the injection orifice may be at least 1 kilopascal (kPa), at least 5 kPa, at least 10 kPa, at least 15 kPa, at least 20 kPa, at least 25 kPa, at least 30 kPa, at least 35 kPa, or at least 40 kPa.

The active flow-control device may be configured to continuously inject the flow-control fluid stream into the boundary layer when the pre-cooler air stream is flowing through the pre-cooler inlet duct.

The active flow-control device may be configured to intermittently inject the flow-control fluid stream into the boundary layer when the pre-cooler air stream is flowing through the pre-cooler inlet duct.

The injection orifice may include at least one of a circular injection orifice, an elongate injection orifice, a slot, and a rectangular slot.

The active flow-control device may be configured to inject the flow-control fluid stream into the boundary layer at a first injection angle as measured in a first plane that is parallel to a surface normal of the flow-directing surface and a second injection angle as measured in a second plane that is parallel to the surface normal direction and perpendicular to the first plane.

The first injection angle may be at least one of: (i) at least 0 degrees, at least 5 degrees, at least 10 degrees, at least 15 degrees, at least 20 degrees, at least 30 degrees, at least 40 degrees, at least 50 degrees, at least 60 degrees, at least **70** degrees, at least **80** degrees, at least **90** degrees, at least **100** degrees, at least **110** degrees, at least **120** degrees, at least **130** degrees, at least **140** degrees, at least **150** degrees, at least **160** degrees, or at least **170** degrees, (ii) less than **180** degrees, less than **170** degrees, less than **160** degrees, less than **150** degrees, less than **140** degrees, less than **130** degrees, less than **120** degrees, less than **110** degrees, less than **100** degrees, less than **90** degrees, less than **80** degrees, less than **70** degrees, less than **60** degrees, less than **50** degrees, less than **40** degrees, less than **30** degrees, less than **20** degrees, less than **15** degrees, less than **10** degrees, or less than **5** degrees, and (iii)a variable first injection angle that varies between any one of (i) and any one of (ii).

The second injection angle may be at least one of: (i) at least **0** degrees, at least **5** degrees, at least **10** degrees, at least **15** degrees, at least **20** degrees, at least **30** degrees, at least **40** degrees, at least **50** degrees, at least **60** degrees, at least **70** degrees, at least **80** degrees, at least **90** degrees, at least **100** degrees, at least **110** degrees, at least **120** degrees, at least **130** degrees, at least **140** degrees, at least **150** degrees, at least **160** degrees, or at least **170** degrees, (ii) less than **180** degrees, less than **170** degrees, less than **160** degrees, less than **150** degrees, less than **140** degrees, less than **130** degrees, less than **120** degrees, less than **110** degrees, less than **100** degrees, less than **90** degrees, less than **80** degrees, less than **70** degrees, less than **60** degrees, less than **50** degrees, less than **40** degrees, less than **30** degrees, less than **20** degrees, less than **15** degrees, less than **10** degrees, or less than **5** degrees, and (iii) a variable second injection angle that varies between any one of (i) and any one of (ii).

The active flow-control device may be configured to inject a plurality of flow-control fluid streams into the boundary layer.

The active flow-control device may be configured to (systematically) vary which of the plurality of flow-control fluid streams is being injected into the boundary layer at a given point in time.

The active flow-control device may be configured to inject the plurality of flow-control fluid streams into the boundary layer via a plurality of injection orifices that is defined by the flow-directing surface.

The plurality of injection orifices may be spaced-apart on the flow-directing surface.

The plurality of injection orifices may include at least one of: (i) at least **4**, at least **8**, at least **9**, at least **12**, at least **18**, at least **24**, at least **36**, at least **72**, at least **90**, at least **120**, at least **180**, at least **270**, or at least **360** injection orifices, and (ii) fewer than **36**, fewer than **72**, fewer than **90**, fewer than **120**, fewer than **180**, fewer than **270**, fewer than **360**, or fewer than **720** injection orifices.

The flow-control fluid stream may include a compressed air stream that optionally is generated by the jet engine.

The flow-control fluid stream may include a synthetic jet that optionally is generated by a synthetic jet generator.

The active flow-control device may include a vortex generator configured to generate a vortex within the boundary layer.

The active flow-control device may include a suction assembly configured to remove a suction stream from the boundary layer.

The active flow-control device may include at least one of a piezoelectric actuator, a shape memory alloy actuator, a diaphragm, a pump, a compressor, and a fan.

In accordance with another embodiment, there is provided a nacelle for a jet engine. The nacelle includes an inlet configured to receive an air stream, and the pre-cooling assembly described above, wherein the pre-cooler inlet duct is fluidly coupled to an inlet of the nacelle.

The pre-cooling assembly may further include a heat exchanger that is configured to receive the pre-cooler air stream from the pre-cooler inlet duct.

In accordance with another embodiment, there is provided an aircraft including an airframe, and the nacelle described above.

In accordance with another embodiment, there is provided a method of resisting boundary layer separation from a flow-directing surface of a pre-cooler inlet duct. The method involves flowing a pre-cooler air stream across the flow-directing surface and through the pre-cooler inlet duct of a jet engine that includes the pre-cooler inlet duct, wherein the flowing includes generating a boundary layer adjacent the flow-directing surface, wherein the boundary layer includes a boundary layer fluid flow; and modifying the boundary layer fluid flow with an active flow-control device to resist separation of the boundary layer from the flow-directing surface.

The boundary layer fluid flow may define a threshold performance, wherein the flow-directing surface defines a radius of curvature, wherein the flowing includes flowing the boundary layer along the radius of curvature, and further wherein the radius of curvature is less than a conventional radius of curvature of a conventional flow-directing surface that produces a comparable threshold performance but that does not utilize the modifying.

The radius of curvature of the flow-directing surface may be less than **90**% less than **80**%, less than **70**%, less than **60**%, less than **50**%, or less than **40**% of the conventional radius of curvature of the conventional flow-directing surface.

The boundary layer fluid flow may define a/the threshold performance, and further wherein a length of the flow-directing surface is less than a conventional length of a/the conventional flow-directing surface that produces a/the comparable threshold performance but that does not utilize the modifying.

The length of the flow-directing surface may be less than **90**% less than **80**%, less than **70**%, less than **60**%, less than **50**%, or less than **40**% of the conventional length of the conventional flow-directing surface.

The modifying may include modifying to resist separation of the boundary layer from the flow-directing surface when an average flow speed of the pre-cooler air stream is at least one of: (i) at least **100** meters/second (m/s), at least **125** m/s, at least **150** m/s, at least **175** m/s, at least **200** m/s, at least **225** m/s, at least **250** m/s, at least **275** m/s, or at least **300** m/s, and (ii) less than **350** m/s, less than **325** m/s, less than **300** m/s, less than **275** m/s, less than **250** m/s, less than **225** m/s, or less than **200** m/s.

The modifying may include injecting a flow-control fluid stream into the boundary layer through an injection orifice that is defined by the flow-directing surface.

A flow speed of the flow-control fluid stream through the injection orifice may be at least one of: (i) at least **100** meters/second (m/s), at least **125** m/s, at least **150** m/s, at least **175** m/s, at least **200** m/s, at least **225** m/s, at least **250** m/s, at least **275** m/s, at least **300** m/s, at least **350** m/s, at least **400** m/s, at least **450** m/s, or at least **500** m/s, and (ii) less than **700** m/s, less than **650** m/s, less than **600** m/s, less than **550** m/s, less than **500** m/s, less than **450** m/s, less than **400** m/s, less than **350** m/s, less than **325** m/s, less than **300** m/s, less than **275** m/s, less than **250** m/s, less than **225** m/s, or less than **200** m/s.

A pressure differential of the flow-control fluid stream across the injection orifice may be at least **1** kilopascal (kPa), at least **5** kPa, at least **10** kPa, at least **15** kPa, at least **20** kPa, at least **25** kPa, at least **30** kPa, at least **35** kPa, or at least **40** kPa.

The injecting may include continuously injecting the flow-control fluid stream while the pre-cooler air stream is flowing through the pre-cooler inlet duct.

The injecting may include intermittently injecting the flow-control fluid stream while the pre-cooler air stream is flowing through the pre-cooler inlet duct.

The injecting may include injecting at a first injection angle as measured in a first plane that is parallel to a surface normal of the flow-directing surface and at a second injection angle as measured in a second plane that is parallel to the surface normal direction and perpendicular to the first plane.

The first injection angle may be at least one of: (i) at least **0** degrees, at least **5** degrees, at least **10** degrees, at least **15** degrees, at least **20** degrees, at least **30** degrees, at least **40** degrees, at least **50** degrees, at least **60** degrees, at least **70** degrees, at least **80** degrees, at least **90** degrees, at least **100** degrees, at least **110** degrees, at least **120** degrees, at least **130** degrees, at least **140** degrees, at least **150** degrees, at least **160** degrees, or at least **170** degrees, (ii) less than **180** degrees, less than **170** degrees, less than **160** degrees, less than **150** degrees, less than **140** degrees, less than **130** degrees, less than **120** degrees, less than **110** degrees, less than **100** degrees, less than **90** degrees, less than **80** degrees, less than **70** degrees, less than **60** degrees, less than **50** degrees, less than **40** degrees, less than **30** degrees, less than **20** degrees, less than **15** degrees, less than **10** degrees, or less than **5** degrees, and (iii) a variable first injection angle that varies between any one of (i) and any one of (ii).

The second injection angle may be at least one of: (i) at least **0** degrees, at least **5** degrees, at least **10** degrees, at least **15** degrees, at least **20** degrees, at least **30** degrees, at least **40** degrees, at least **50** degrees, at least **60** degrees, at least **70** degrees, at least **80** degrees, at least **90** degrees, at least **100** degrees, at least **110** degrees, at least **120** degrees, at least **130** degrees, at least **140** degrees, at least **150** degrees, at least **160** degrees, or at least **170** degrees, (ii) less than **180** degrees, less than **170** degrees, less than **160** degrees, less than **150** degrees, less than **140** degrees, less than **130** degrees, less than **120** degrees, less than **110** degrees, less than **100** degrees, less than **90** degrees, less than **80** degrees, less than **70** degrees, less than **60** degrees, less than **50** degrees, less than **40** degrees, less than **30** degrees, less than **20** degrees, less than **15** degrees, less than **10** degrees, or less than **5** degrees, and (iii) a variable second injection angle that varies between any one of (i) and any one of (ii).

The method may further include directing a compressed air stream (that optionally is generated by the jet engine) through the injection orifice to generate the flow-control fluid stream.

The method may further include generating the flow-control fluid stream with a synthetic jet generator.

The injecting may include injecting a plurality of flow-control fluid streams into the boundary layer.

The injecting may include (systematically) varying which of the plurality of flow-control fluid streams is being injected into the boundary layer at a given point in time.

The injecting may include injecting the plurality of flow-control fluid streams in a spaced-apart manner across the flow-directing surface.

The plurality of flow-control fluid streams may include at least one of: (i) at least **8**, at least **9**, at least **12**, at least **18**, at least **24**, at least **36**, at least **72**, at least **90**, at least **120**, at least **180**, at least **270**, or at least **360** injection orifices, and (ii) fewer than **36**, fewer than **72**, fewer than **90**, fewer than **120**, fewer than **180**, fewer than **270**, fewer than **360**, or fewer than **720** injection orifices.

The modifying may include generating a vortex within the boundary layer with a vortex generator.

The modifying may include removing a suction stream from the boundary layer with a suction assembly.

The modifying includes modifying with at least one of a piezoelectric actuator, a shape memory alloy actuator, a diaphragm, a pump, a compressor, and a fan.

As used herein, the terms “selective” and “selectively,” when modifying an action, movement, configuration, or other activity of one or more components or characteristics of an apparatus, mean that the specific action, movement, configuration, or other activity is a direct or indirect result of user manipulation of an aspect of, or one or more components of, the apparatus.

As used herein, the terms “adapted” and “configured” mean that the element, component, or other subject matter is designed and/or intended to perform a given function. Thus, the use of the terms “adapted” and “configured” should not be construed to mean that a given element, component, or other subject matter is simply “capable of” performing a given function but that the element, component, and/or other subject matter is specifically selected, created, implemented, utilized, programmed, and/or designed for the purpose of performing the function. It is also within the scope of the present disclosure that elements, components, and/or other recited subject matter that is recited as being adapted to perform a particular function may additionally or alternatively be described as being configured to perform that function, and vice versa. Similarly, subject matter that is recited as being configured to perform a particular function may additionally or alternatively be described as being operative to perform that function.

The various disclosed elements of apparatuses and steps of methods disclosed herein are not required to all apparatuses and methods according to the present disclosure, and the present disclosure includes all novel and non-obvious combinations and subcombinations of the various elements and steps disclosed herein. Moreover, one or more of the various elements and steps disclosed herein may define independent inventive subject matter that is separate and apart from the whole of a disclosed apparatus or method. Accordingly, such inventive subject matter is not required to be associated with the specific apparatuses and methods that are expressly disclosed herein, and such inventive subject matter may find utility in apparatuses and/or methods that are not expressly disclosed herein.

EMBODIMENTS IN WHICH AN EXCLUSVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A pre-cooler inlet duct for receiving and directing a pre-cooler air stream into a heat exchanger, the pre-cooler inlet duct comprising:

a flow-directing surface that defines at least a portion of the pre-cooler inlet duct and an injection orifice in communication with the portion of the pre-cooler inlet duct, the flow-directing surface being shaped to direct the pre-cooler air stream into the heat exchanger; and

an active flow-control device which injects, through the injection orifice, at an injection angle measured in a plane parallel to a surface normal direction of the flow-directing surface, a flow-control fluid stream into a boundary layer adjacent the flow-directing surface to modify a boundary layer fluid flow within the boundary layer and to resist separation of the boundary layer from the flow-directing surface when the pre-cooler air stream flows through the pre-cooler inlet duct, and

wherein the injection orifice periodically varies the injection angle between an upper angle limit and a lower angle limit.

CA 2897254 2017-10-20

2. The pre-cooler inlet duct of claim **1**, wherein the active flow-control device injects the flow-control fluid stream when an average pre-cooler air stream flow speed through the pre-cooler inlet duct is at least **50** meters/second (m/s) and less than **350** m/s.

3. The pre-cooler inlet duct of claim **1** or claim **2**, wherein the injection orifice forms a portion of a sweeping jet.

4. The pre-cooler inlet duct of any one of claims **1** to **3**, wherein the active flow-control device continuously injects the flow-control fluid stream into the boundary layer when the pre-cooler air stream is flowing through the pre-cooler inlet duct.

5. The pre-cooler inlet duct of any one of claims **1** to **4**, wherein the active flow-control device intermittently injects the flow-control fluid stream into the boundary layer when the pre-cooler air stream is flowing through the pre-cooler inlet duct.

6. The pre-cooler inlet duct of any one of claims **1** to **5**, wherein the injection orifice comprises a plurality of injection orifices, and the active flow-control device injects a plurality of flow-control fluid streams into the boundary layer through respective ones of the plurality of injection orifices.

7. The pre-cooler inlet duct of claim **6**, wherein the active flow-control device varies which of the plurality of flow-control fluid streams is being injected into the boundary layer at a given point in time.

8. The pre-cooler inlet duct of any one of claims **1** to **7**, wherein the active flow-control device further comprises a vortex generator for generating a vortex within the boundary layer.

9. The pre-cooler inlet duct of any one of claims **1** to **8**, wherein the active flow-control device further comprises a suction assembly that removes a suction stream from the boundary layer.

10. A nacelle for a jet engine, comprising:

an inlet for receiving an air stream; and

a pre-cooling assembly including the pre-cooler inlet duct of any one of claims **1** to **9**, wherein the pre-cooler inlet duct is fluidly coupled to the inlet of the nacelle.

11. The nacelle of claim **10**, further comprises a compressor positioned within the nacelle and able to receive the air stream from the inlet and to pressurize the air stream to generate a compressed air stream.

12. The nacelle of claim **11**, wherein the compressor is able to provide a portion of the compressed air stream that comprises the pre-cooler air stream to the pre-cooler inlet duct at an average flow speed of at least at least **50** meters/second (m/s) and less than **350** m/s.

13. A jet engine, comprising the nacelle of any one of claims **10** to **12**.

14. A method of resisting boundary layer separation from a flow-directing surface of a pre-cooler inlet duct, the method comprising:

flowing a pre-cooler air stream across the flow-directing surface and through the pre-cooler inlet duct, wherein the flowing includes generating a boundary layer adjacent the flow-directing surface, and further wherein the boundary layer includes a boundary layer fluid flow;

modifying the boundary layer fluid flow with an active flow-control device to resist separation of the boundary layer from the flow-directing surface by:

injecting a flow-control fluid stream, through an injection orifice defined by the flow-directing surface, at an injection angle measured in a plane parallel to a surface normal direction of the flow-directing surface, such that the flow-control fluid stream is injected into the boundary layer; and

periodically varying, by the injection orifice, the injection angle between an upper angle limit and a lower angle limit.

15. The method of claim **14**, wherein the injecting includes at least one of:

(i) continuously injecting the flow-control fluid stream while the pre-cooler air stream is flowing through the pre-cooler inlet duct; and

(ii) intermittently injecting the flow-control fluid stream while the pre-cooler air stream is flowing through the pre-cooler inlet duct.

16. The method of claim **14** or claim **15**, wherein the method further includes at least one of:

(i) directing an injection compressed air stream through the injection orifice to generate the flow-control fluid stream; and

(ii) generating the flow-control fluid stream with a synthetic jet generator.

17. The method of any one of claims **14** to **16**, wherein the injection orifice includes a plurality of injection orifices defined by the flow-control surface, and wherein the injecting includes injecting a plurality of flow-control fluid streams into the boundary layer through respective ones of the plurality of injection orifices.

18. The method of claim **17**, wherein the injecting includes varying which of the plurality of flow-control fluid streams is being injected into the boundary layer at a given point in time.

19. The method of any one of claims **14** to **18**, wherein the modifying includes at least one of:

(i) generating a vortex within the boundary layer with a vortex generator; and

(ii) removing a suction stream from the boundary layer with a suction assembly.

20. The method of any one of claims **14** to **19**, wherein the method further includes:

receiving an airstream at an inlet of a nacelle of a jet engine; and compressing the air stream with a compressor of the jet engine to pressurize the air stream to generate a compressed air stream.

21. The method of claim **20**, wherein the flowing comprises flowing a portion of the compressed air stream as the pre-cooler air stream.

22. A jet engine, comprising:

a nacelle including an inlet for receiving an air stream;

a compressor positioned within the nacelle and for receiving the air stream and pressurizing the air stream to generate a compressed air stream;

a pre-cooler inlet duct positioned within the nacelle and for receiving a portion of the compressed air stream as a pre-cooler air stream; and

a heat exchanger positioned within the nacelle and for receiving the pre-cooler air stream, wherein the pre-cooler inlet duct is further for directing the pre-cooler air stream into the heat exchanger; and

further wherein the pre cooler inlet duct includes:

(i) a flow-directing surface that defines at least a portion of the pre-cooler inlet duct and is shaped to direct the pre-cooler air stream into the heat exchanger; and

(ii) an active flow-control device which injects a flow-control fluid stream into a boundary layer, through an injection orifice that is defined by the flow-directing surface, to modify the boundary layer fluid flow within a boundary layer adjacent the flow-directing surface to resist separation of the boundary layer from the flow-directing surface when the pre-cooler air stream flows through the pre-cooler inlet duct, and further wherein the injection orifice injects the flow-control fluid stream at an injection angle, which is measured in a plane that is parallel to a surface normal direction of the flow-directing surface, that periodically varies between a lower angle limit and an upper angle limit.

23. The jet engine of claim **22**, wherein the compressor provides the portion of the compressed air stream that comprises the pre-cooler air stream to the pre-cooler inlet duct at an average flow speed of at least **100** meters/second (m/s) and less than **350** m/s, and further wherein the active flow-control device resists separation of the boundary layer from the flow-directing surface.

CA 2897254 2017-10-20

24. The jet engine of claim **22** or **23**, wherein the active flow-control device continuously injects the flow-control fluid stream into the boundary layer when the pre-cooler air stream is flowing through the pre-cooler inlet duct.

25. The jet engine of claim **22** or **23**, wherein the active flow-control device intermittently injects the flow-control fluid stream into the boundary layer when the pre-cooler air stream is flowing through the pre-cooler inlet duct.

26. The jet engine of any one of claims **22** to **25**, wherein the active flow-control device injects a plurality of flow-control fluid streams into the boundary layer.

27. The jet engine of claim **26**, wherein the active flow-control device varies which of the plurality of flow-control fluid streams is being injected into the boundary layer at a given point in time.

28. The jet engine of any one of claims **22** to **27**, wherein the active flow-control device further comprises a vortex generator for generating a vortex within the boundary layer.

29. The jet engine of any one of claims **22** to **28**, wherein the active flow-control device further comprises a suction assembly that removes a suction stream from the boundary layer.

CA 2897254 2017-10-20

30. A method of resisting boundary layer separation from a flow-directing surface of a pre-cooler inlet duct of a jet engine, the method comprising:

receiving an air stream with an inlet of a nacelle of the jet engine;

compressing the air stream with a compressor of the jet engine to pressurize the air stream and generate a compressed air stream;

flowing a portion of the compressed air stream, as a pre-cooler air stream, across the flow-directing surface of the pre-cooler inlet duct and through the pre-cooler inlet duct, wherein the flowing includes generating a boundary layer adjacent the flow-directing surface, and further wherein the boundary layer includes a boundary layer fluid flow; and

modifying the boundary layer fluid flow with an active flow-control device to resist separation of the boundary layer from the flow-directing surface of the pre-cooler inlet duct, wherein the modifying includes injecting a flow-control fluid stream into the boundary layer through an injection orifice that is defined by the flow-directing surface, wherein the injection orifice injects the flow-control fluid stream at an injection angle, which is measured in a plane that is parallel to a surface normal direction of the flow-directing surface, and further wherein the injecting includes periodically varying the injection angle between a lower angle limit and an upper angle limit.

31. The method of claim **30**, wherein the injecting includes at least one of:

(i) continuously injecting the flow-control fluid stream while the pre-cooler air stream is flowing through the pre-cooler inlet duct; and

(ii) intermittently injecting the flow-control fluid stream while the pre-cooler air stream is flowing through the pre-cooler inlet duct.

32. The method of claim **30** or **31**, wherein the method further includes directing an injection compressed air stream through the injection orifice to generate the flow-control fluid stream.

33. The method of any one of claims **30** to **32**, wherein the injecting includes injecting a plurality of flow-control fluid streams into the boundary layer, and further wherein the injecting includes varying which of the plurality of flow-control fluid streams is being injected into the boundary layer at a given point in time.

34. The method of any one of claims **30** to **33**, wherein the modifying further includes at least one of:

(i) generating a vortex within the boundary layer with a vortex generator; and

CA 2897254 2017-10-20

(ii) removing a suction stream from the boundary layer with a suction assembly.

35. The method of any one of claims **30** to **34**, wherein:

(i) the flowing includes flowing the pre-cooler inlet stream at an average flow speed of at least **100** meters/second (m/s) and less than **350** m/s; and

(ii) the modifying resists separation of the boundary layer from the flow-directing surface.

13-2378

1/7

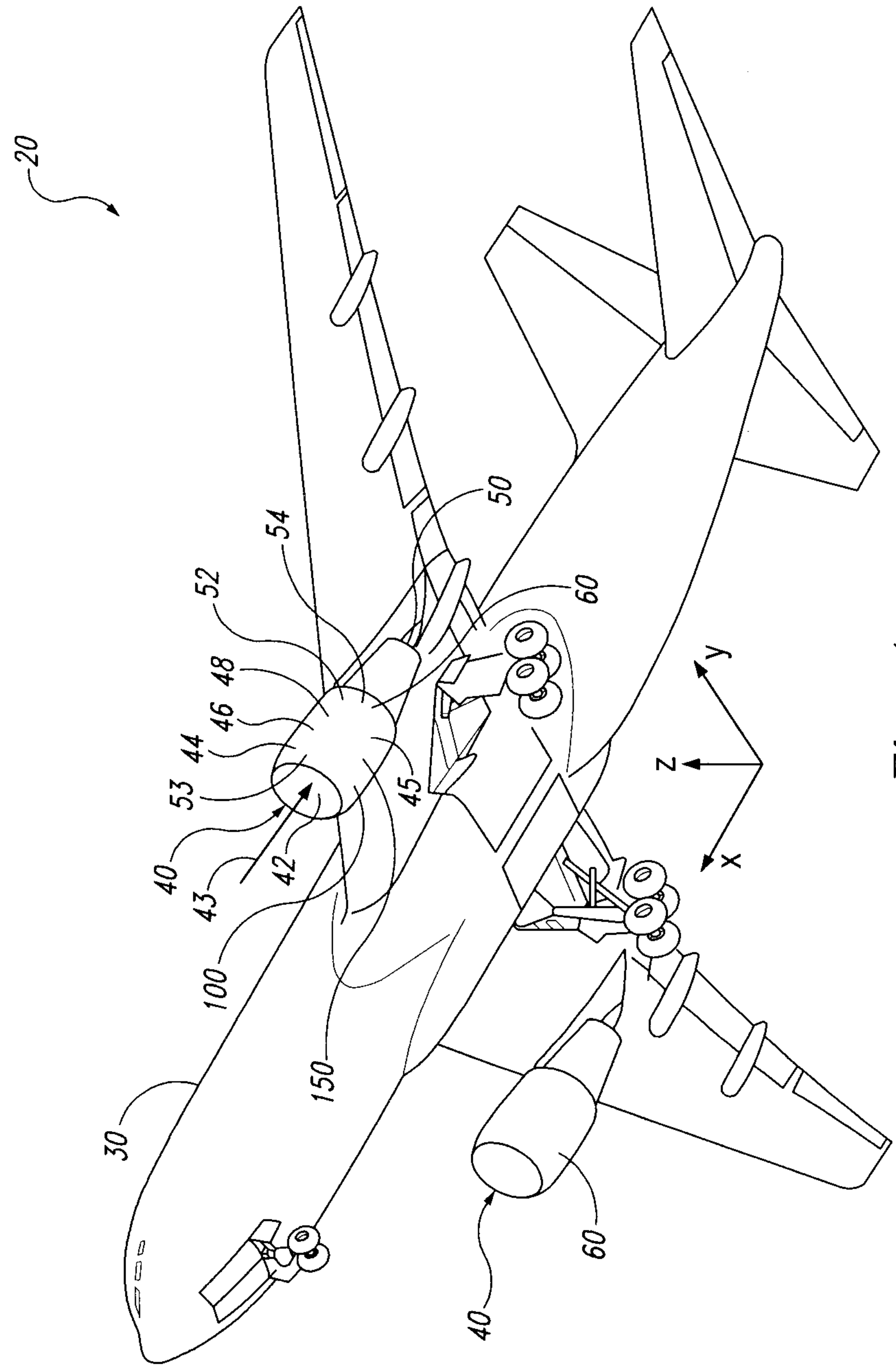


Fig. 1

13-2378

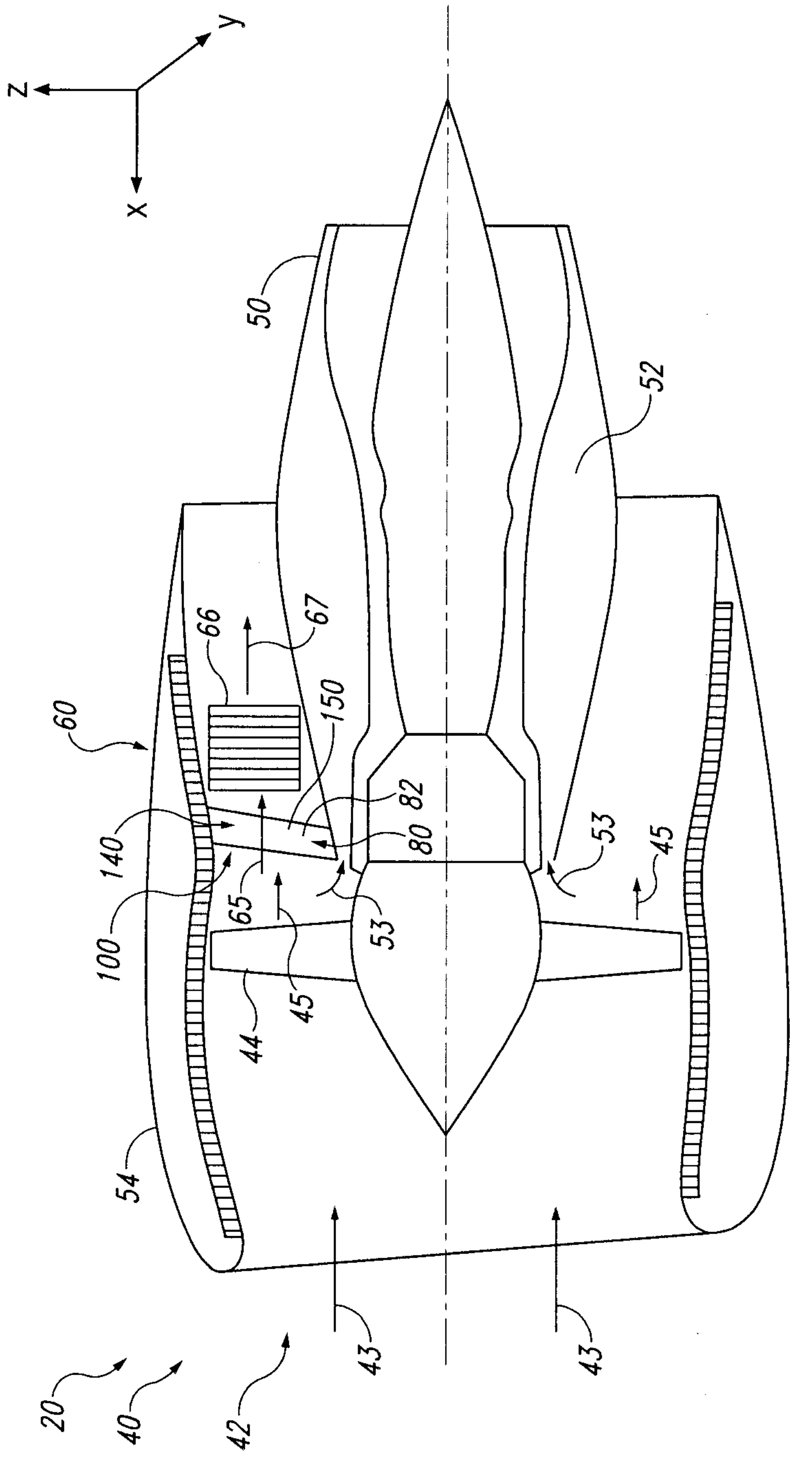


Fig. 2

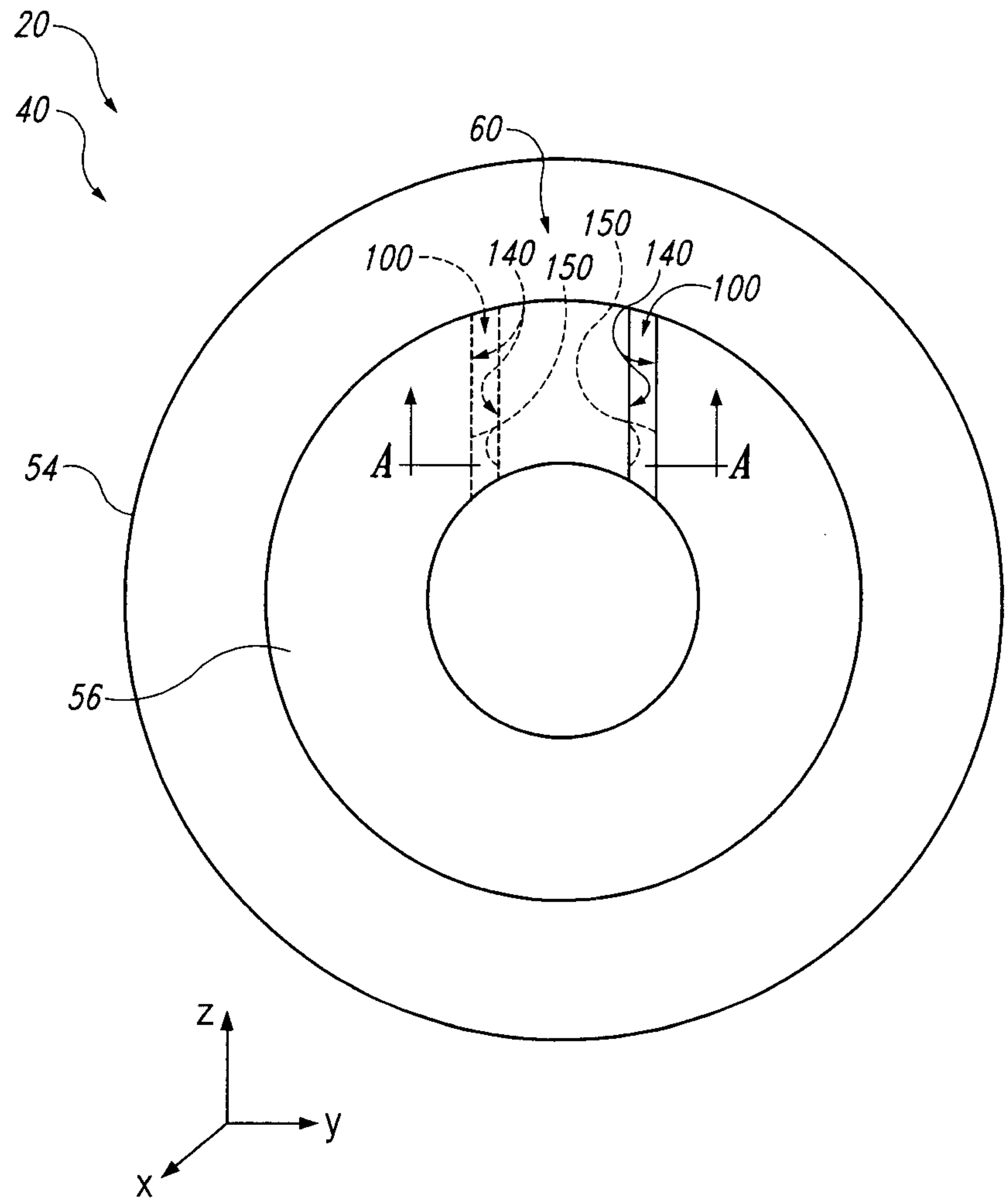


Fig. 3

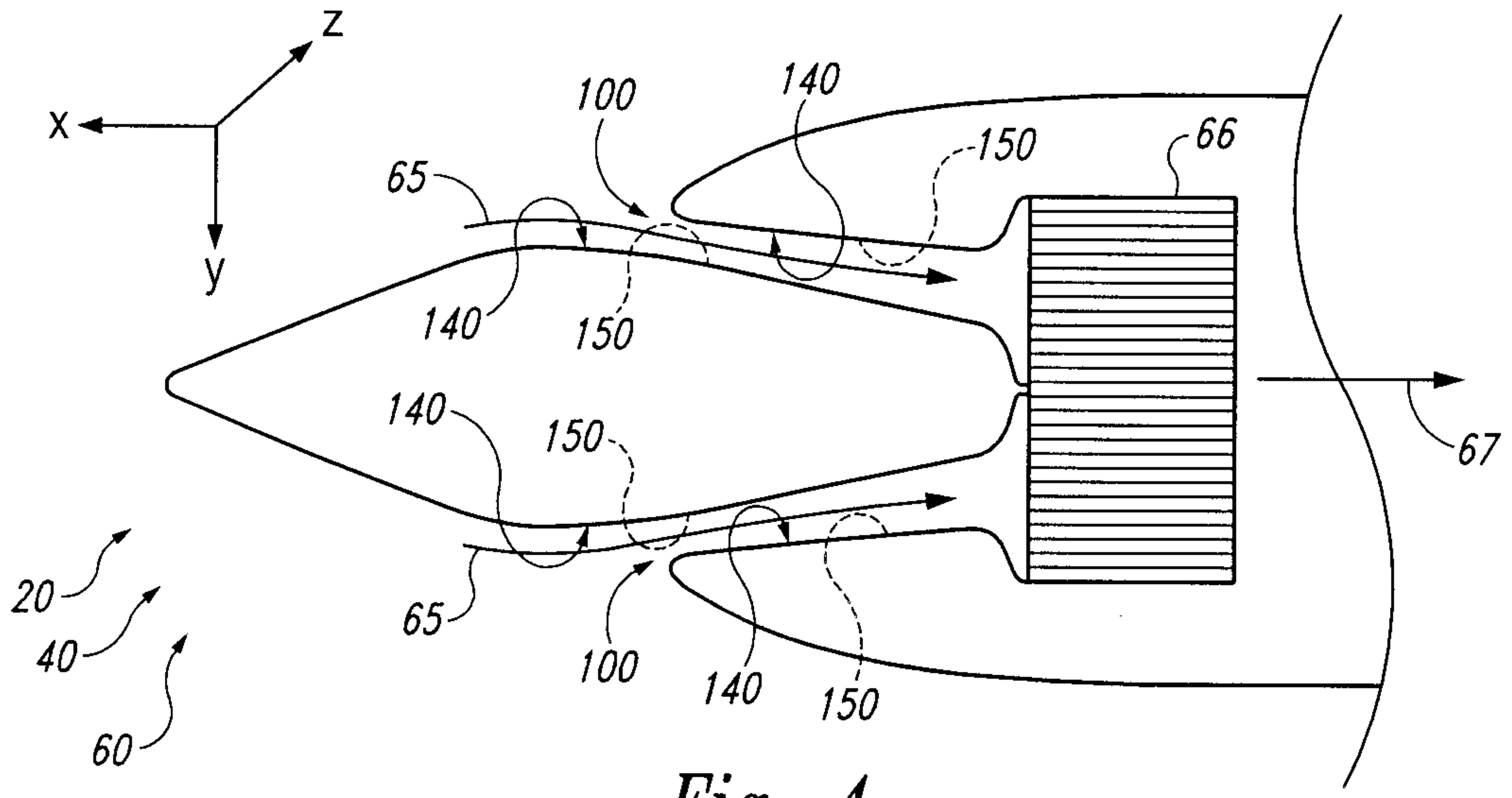

z
x
y
100
140
65
150
66
140
150
140
150
67
20
65
40
100
140
150
60

Fig. 4

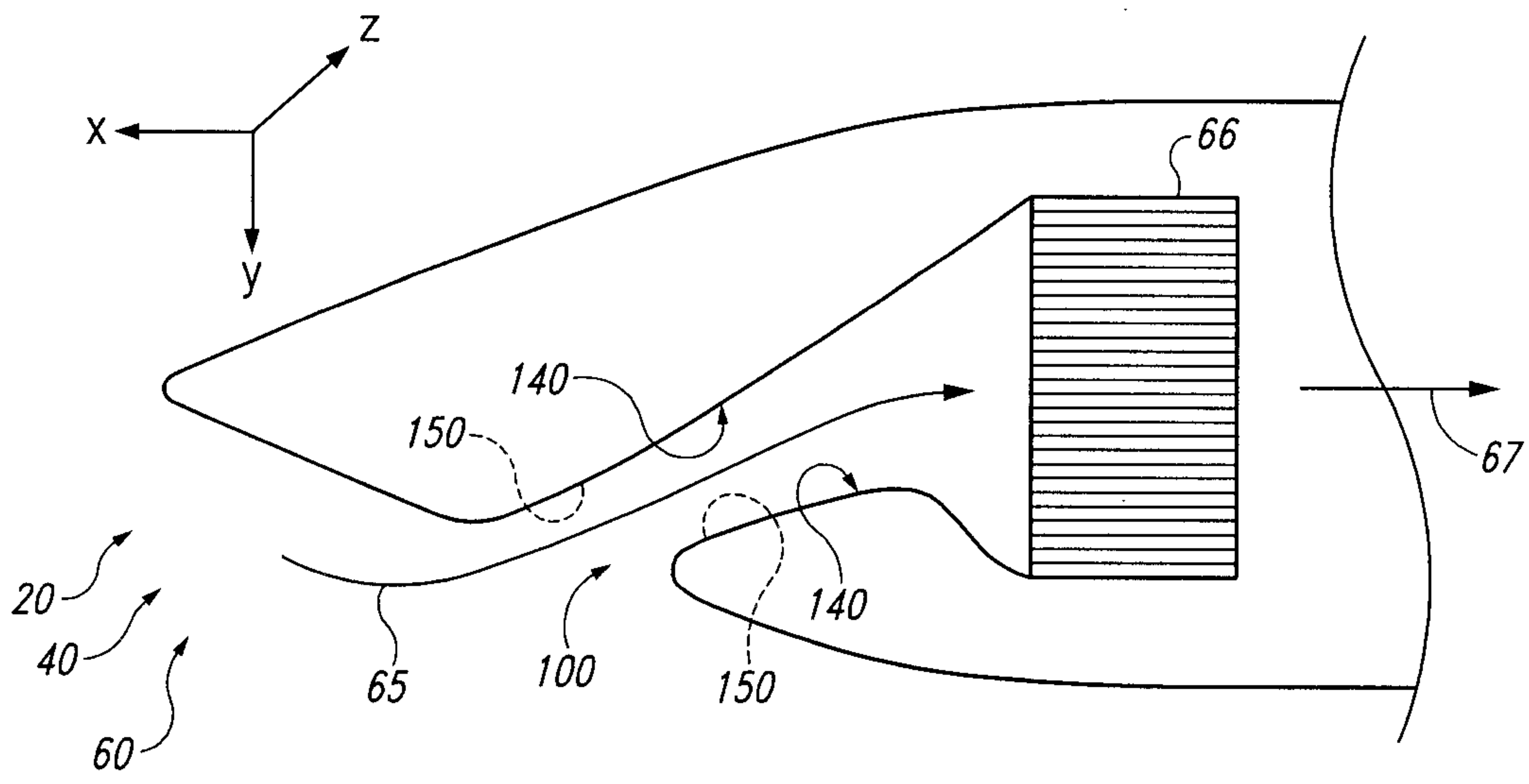

z
x
y
66
140
150
67
20
40
140
65
100
150
60

Fig. 5

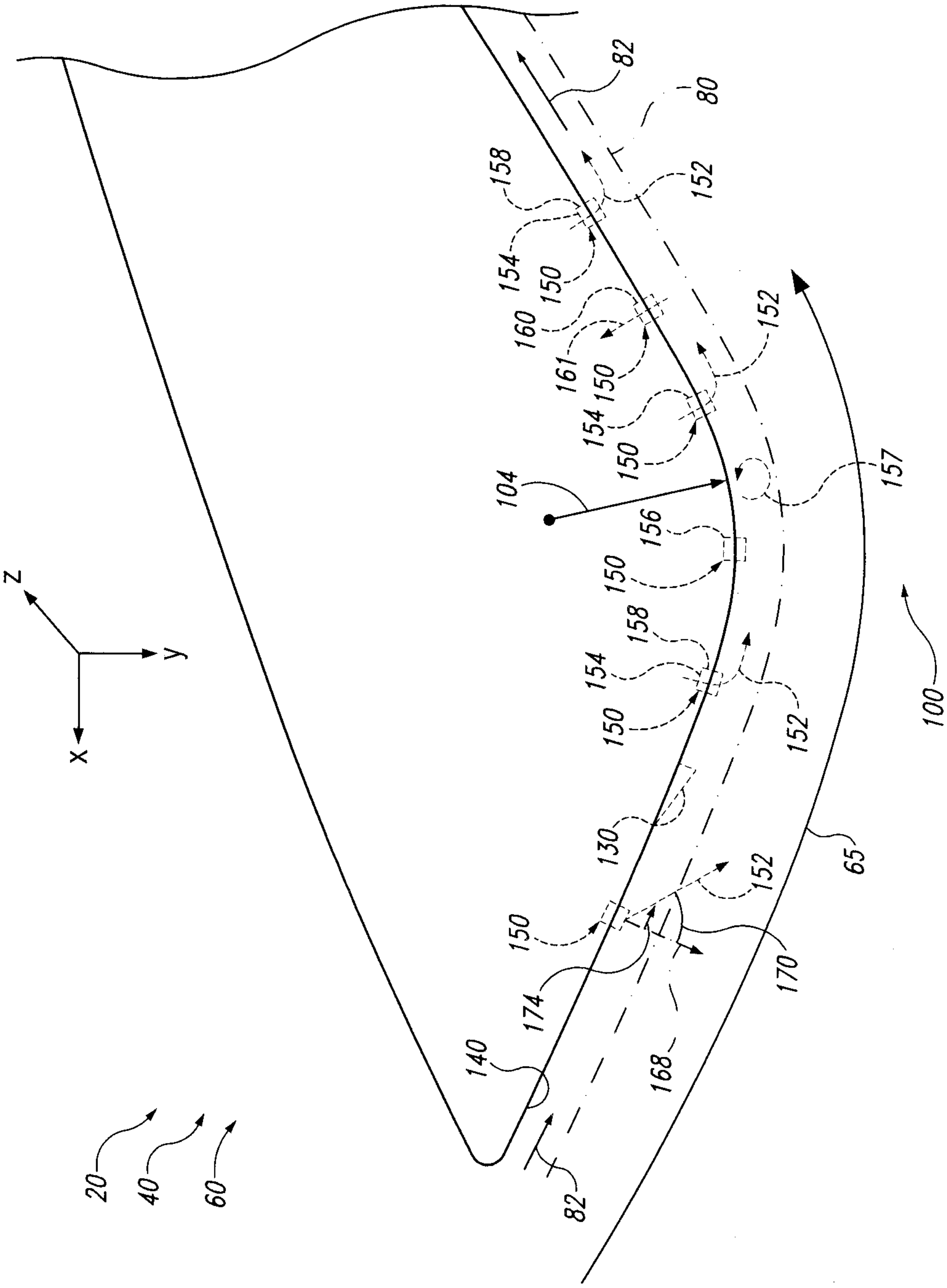

82
80
158
152
154
150
160
161
152
150
154
150
157
104
156
150
158
154
150
152
130
152
150
174
170
168
140
82
65
100
z
y
x
20
40
60

Fig. 6

13-2378

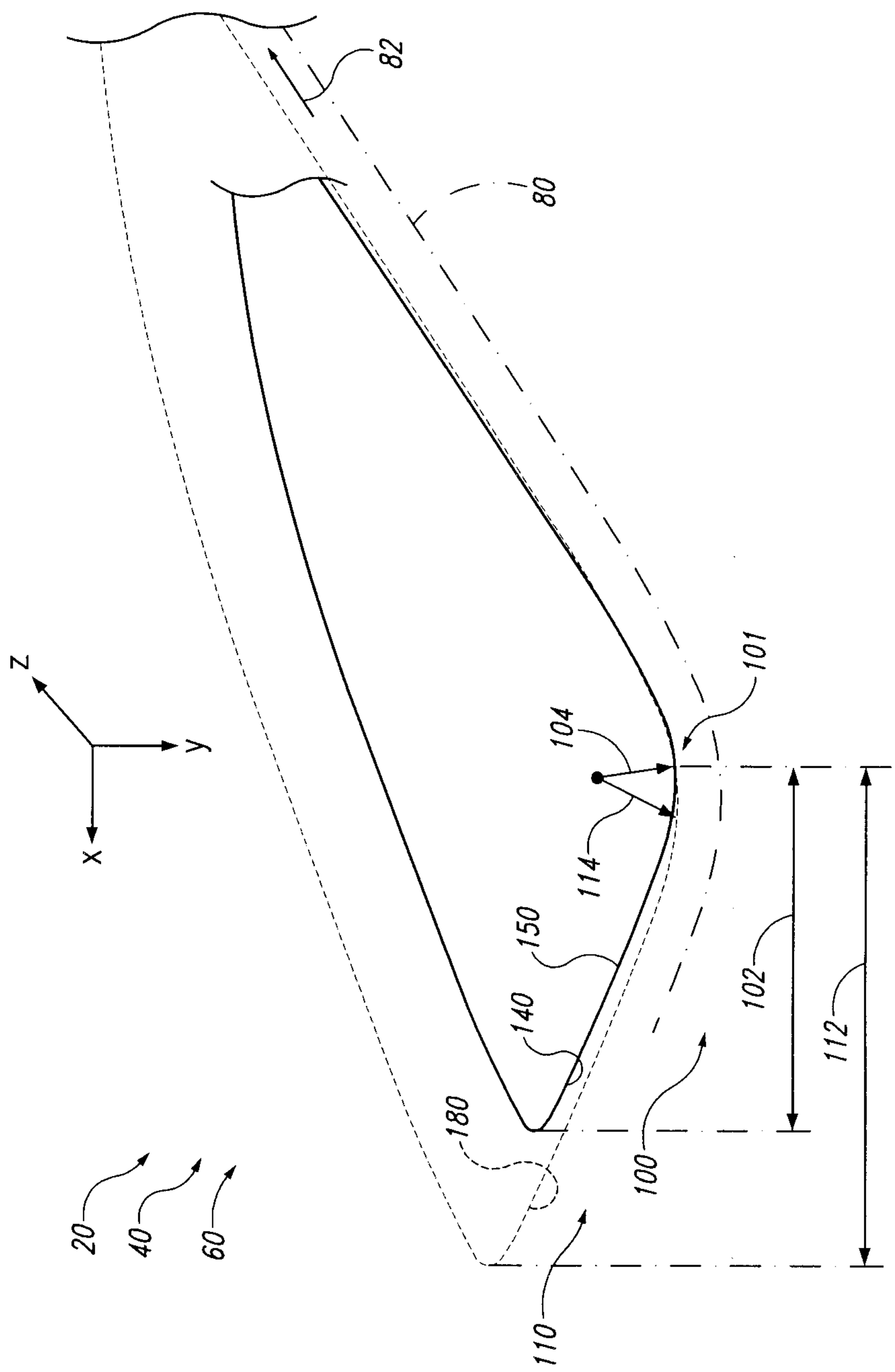


Fig. 7

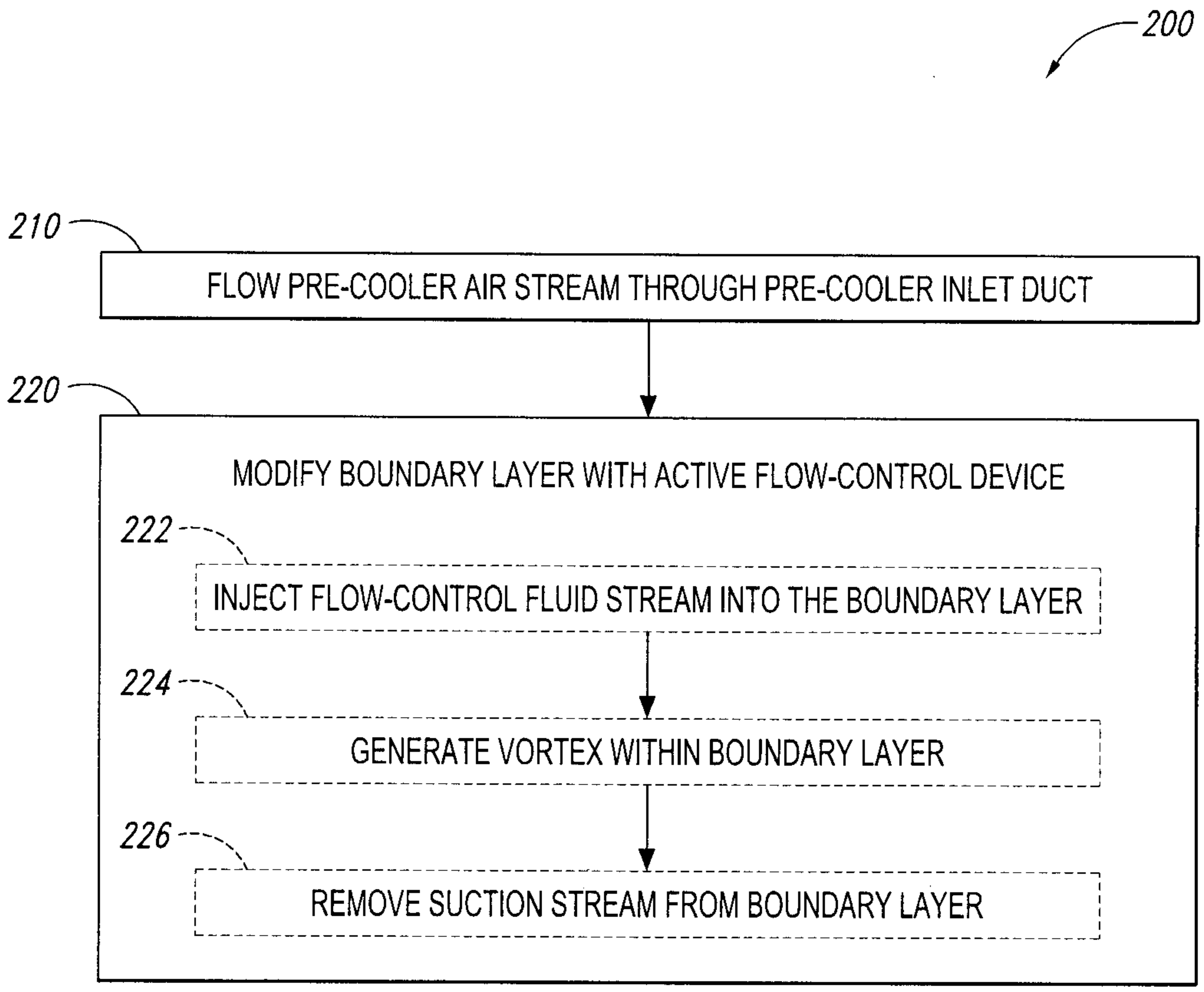
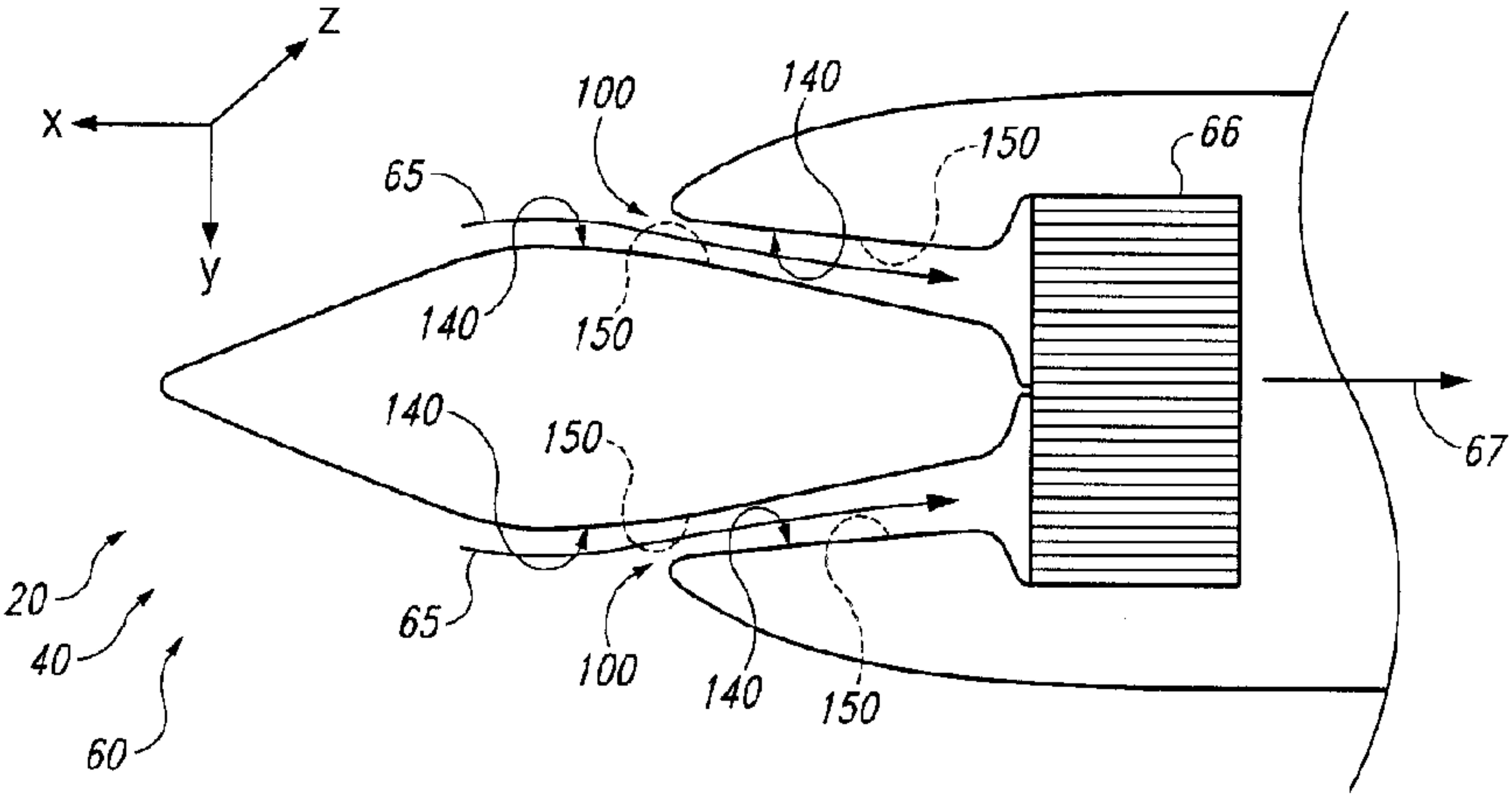

200
210
FLOW PRE-COOLER AIR STREAM THROUGH PRE-COOLER INLET DUCT
220
MODIFY BOUNDARY LAYER WITH ACTIVE FLOW-CONTROL DEVICE
222
INJECT FLOW-CONTROL FLUID STREAM INTO THE BOUNDARY LAYER
224
GENERATE VORTEX WITHIN BOUNDARY LAYER
226
REMOVE SUCTION STREAM FROM BOUNDARY LAYER

Fig. 8



x
y
z
100
140
150
66
65
140
150
140
150
67
20
40
65
100
140
150
60