



(51) International Patent Classification:

B64C 21/08 (2006.01) *B64C 21/06* (2006.01)
B64C 21/02 (2006.01) *B64D 29/00* (2006.01)
B64C 21/04 (2006.01) *B64D 33/02* (2006.01)

(21) International Application Number:

PCT/US2019/063764

(22) International Filing Date:

27 November 2019 (27.11.2019)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

62/771,768 27 November 2018 (27.11.2018) US

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(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV,

(54) Title: AERODYNAMIC FLOW CONTROL SYSTEMS AND METHODS

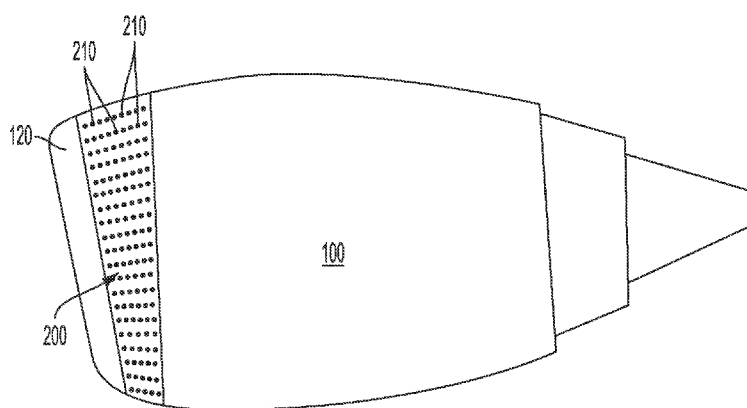


FIG. 1

(57) Abstract: An aerodynamic flow control system in proximity to the nacelle inlet to provide "virtual" shaping of the nacelle's flow surface. The aerodynamic flow control is adjustable so that it can be continuously and adaptively optimized for a range of operating stages throughout the flight envelope.



MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM,
TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW,
KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *of inventorship (Rule 4.17(iv))*

Published:

— *with international search report (Art. 21(3))*

AERODYNAMIC FLOW CONTROL SYSTEMS AND METHODS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of US Provisional Application No. 62/771,768 filed 27 November 2018 the entire contents and substance of which is hereby incorporated by
5 reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention is generally related to aerodynamic design, and more particularly to nacelle inlet flow control strategies based on controllable air flow between the
10 windward outer and inner surfaces of the nacelle.

2. Description of Related Art

Control of a moving body through media traditionally has been achieved by employing a moving control surface to the moving body. The moving control surface is a physical obstruction, such as a flap or rudder, that alters the media flow around the moving
15 body, thereby achieving control over the surface. In aerodynamics, the media is air/atmosphere, the moving control surface is an aerodynamic surface, and the controlled movements include roll, pitch, and yaw movements.

Specifically, aircraft engine nacelles encounter a range of disparate operating stages including ground taxi, takeoff, climb, cruise, descent, and landing. The nacelle inlet is
20 normally optimized for cruise, so its design is therefore compromised for other operational stages of the flight. Consequently, selecting the aerodynamic design that is best suited for all aspects of a flight is extremely difficult. A successful implementation must present varying aerodynamic designs for the very same element as it moves through all stages of operation.

For example, the performance of aircraft engines close to the ground (taxi, takeoff,
25 and landing) can be strongly impacted by the presence of the ground plane and by crosswind that can significantly alter air intake in proximity to the nacelle inlet. The presence of a crosswind can lead to the formation of a fuselage vortex, inlet flow separation, and, when coupled with ground effect, the formation of a ground vortex that may cause ingestion of debris into the engine.

30 Of particular note is a nacelle inlet flow separation that can occur for a variety of

reasons, for example, in the presence of crosswind at low speed or during climb at steep angles. The formation of a highly unsteady separation bubble on the windward edge can produce vortex shedding and lead to interactions with the compressor blades, which can cause blade damage and even compressor stall. Furthermore, the separation bubble also
5 decreases the effective cross-sectional area of the nacelle inlet, and hence the mass flow rate through the engine for a fixed engine pressure ratio (EPR).

Upon characterization of the nacelle inlet flow at varying mass flow rates and crosswind speeds, it is clear that solutions to alleviate some of the detrimental effects of the crosswind, predominantly expressed in terms of the total pressure losses (and the mass flow
10 reduction) and distortions are needed.

It remains a challenge to aerodynamically design a nacelle that is optimally suited for different aspects of a flight. It is thus an intention of the present invention to provide aerodynamic flow control based on controllable air flow between the windward outer and inner surfaces of the nacelle for mitigation of the known adverse effects of flow separation on the
15 surface of the nacelle inlet section, that enables effective strategies for utilization of advanced, more efficient nacelle configurations.

BRIEF SUMMARY OF THE INVENTION

Briefly described, in a preferred form, the present invention comprises aerodynamic flow control systems and methods that provides a scalable approach to engine operation by
20 distributed fluidic modification of the apparent aerodynamic shape of the surfaces in proximity to an aircraft engine. In many instances, this is the nacelle in general, and the nacelle inlet more specifically.

The present invention comprises virtual aerosurface shaping systems and methods. Robust control of attached and separated flows is engendered by leveraging the operating
25 condition environment of the aerosurface. For example, the aerosurface will experience flow dynamics imparted by the thrust of the engine, crosswind issues, weather-related factors, as well as many others. Each of these conditions can change over time, without movement of the aerosurface (a plane awaiting takeoff – not moving – will still present the engine with changes in weather, crosswind, etc.), and/or can and will change over time as the aerosurface
30 experiences the range of disparate operating stages including ground taxi, takeoff, climb, cruise, descent, and landing.

In an exemplary embodiment, the present invention controls airflows near the aerosurface to alter its aerodynamic shape and thereby the aerodynamic forces and moments without mechanical control surfaces. It provides aerodynamic flow control in proximity to the nacelle inlet that leads to “virtual” shaping of the nacelle’s flow surface. The aerodynamic flow control on the one hand is passive (comprising ports for air transport between high- and low-pressure regions), and active (as the number, placement, size of the ports is controllable), so the present invention is adjustable to be continuously and adaptively optimizing the virtual aerosurface (nacelle) shaping for a range of operating stages throughout the flight envelope.

This can be especially important in the ground state, where the presence of a crosswind can lead to the formation of a fuselage vortex, inlet flow separation, and, when coupled with ground effect, the formation of a ground vortex that may cause ingestion of debris into the engine. The present invention can include ports at the bottom section of the nacelle that, when intelligently controlled, ameliorate the creation of such ground vortices. The ports can be located in any area where configurable air flow control is beneficial.

The present invention makes use of passive porosity for aerodynamic flow control, exploiting differences in the inherent pressure distribution induced by fluid motion over a surface. Passive porosity *per se* is known and has been investigated for many years. In its typical application, fluid is transported from high to low pressure through passive porosities. The term “passive” used in this sense relates to the natural state of gas, that without interference, will move from high-pressure areas to low-pressure areas. And the bigger the difference between the pressures, the faster the gas will move from the high to the low pressure.

While such passive porosity systems are known, and work simply if there is flow path provided from high to low pressure, the system can nonetheless be “actively” controlled. Here, while the state of the physical system is passive (the flow occurs naturally), the flow-handling can be actively managed. For example, a passive system can comprise a plurality of inlet ports and outlet ports. In a passive system, an “inlet port” is the port at higher pressure than the “outlet port”. Thus, an inlet port can become an outlet port upon pressure changes experiences on the two surfaces of the port.

Yet, the number/location/patterning/etc. of the plurality of inlet and outlet ports can be actively controlled. For example, valves can be located between ports that upon actuation,

can inhibit the amount of flow. Or two surfaces/plates of ports can be moved relative one another, where such movement between the surfaces closes/opens a flow path between unaligned/aligned ports of the surfaces, respectively.

5 The ports can have any number of shapes, sizes, alignment, patterning, etc. to enable the present invention to effectively carry out the beneficial aspects. That includes that the ports can be designed so they do not alter the apparent aerodynamics of the structure even if the inventive flow system is not being used. Ports and/or flow paths can be open, closed, or anywhere in between, but not require that the ports themselves, at the surface, be completely covered in order to present an aerodynamic surface that is airworthy. They can be sized and
10 located such that even if they present surface openings, they do not contribute to detrimental flight conditions.

The present invention uses intelligent control of flow path to optimize virtual aerosurface shaping. It does not depend on physical structures to generate vortexes, not does it use physical structures to disrupt or change boundary layer flows. In essence, it uses the
15 absence of material, ports for air flow, to provide real-time adaptation of the virtual airfoil surface.

The present invention's provision of virtual surface shaping helps overcome adverse inlet flow effects such as encountered by crosswind, and also enables optimization of the effectiveness of the inlet for different flow speeds including cruise.

20 It uses environmental conditions of the engine, crossflows, etc. and enables air to move from high to low pressure in order to minimize or eliminate inlet flow separation. The present invention does not create flow via an external element, for example, a pump or other mechanism to create flow. It adapts the placement, amount, and velocity, to name a few, of air flow from external the nacelle, to internal the nacelle.

25 Before considering the specific case of nacelle inlet flow conditions in crosswind, its operation is verified in its absence, i.e., with only the inlet flow being drawn by the suction blower from the stagnant surrounding air. As expected, the flow is uniformly drawn into the inlet from all directions, and only the axially-aligned inflow traces are captured in segmented surface oil-flow visualizations.

30 Uninterrupted outer flow turning over the inlet lip of the nacelle is also verified by the PIV measurements, where only a slight thickening of the boundary layer is seen, as the flow manages the turn. Finally, the total pressure profiles at all azimuthal locations indicate that

the only total pressure deficit is seen along the nacelle wall region, which is attributed to the boundary layer. Altogether, everything points to expected flow intake in the absence of crosswind.

5 The present invention is a flow control approach utilizing the existing high-pressure differential between the outer windward nacelle surface, having the high stagnation pressure, and the inner surface of the inlet lip of the nacelle, creating a high-pressure differential, which prompts an application of autonomous aerodynamic flow control. The aerodynamic flow control “pulls” air from the outside of the inlet that then moves along the wall of the inner surface of the nacelle. This changes the “effective inner surface shape” (virtual shape)
10 that the incoming flow sees - which changes the flow behavior.

When viewed against a conventional nacelle inlet having no inlet/outlet ports, the present aerodynamic flow control leads to a reduction in cross stream total pressure deficit and concomitantly to a 3% increase in the inlet’s mass flow rate (at a fixed operating point) at crosswind speeds of 30 to 35 knots.

15 The present aerodynamic flow control alleviates separation and mitigate distortion losses. The present aerodynamic flow control-crossflow interaction alters apparent aerodynamic shape of the element to which the present invention is applied. In a specific embodiment, being the nacelle.

20 Use of the present invention reduces fuel consumption, pollution and other harmful effects because it presents a more aerodynamic virtual surface in real-time, leading to less drag and lower efficiencies. So when viewed against a base statistic like the amount of thrust/power/fuel consumption with a conventional airfoil that does not incorporate the present invention, the present invention enables more thrust, using less power, and contributing less pollution than the conventional, similarly-shaped airfoil.

25 Actuation mechanical energy is derived from nacelle flow, driven by the pressure difference across the nacelle. It is thus a passive system in this sense. The present aerodynamic flow control requires no engine (or compressor) air and obviates the need for complex plumbing.

30 The present aerodynamic flow can be dynamically regulated by, for example, low-power integrated actuators. It is thus an active system in this sense.

Thus, in a first exemplary embodiment, in a method of aerodynamic control through media including operating an engine at power levels through a range of operating stages,

wherein the engine is within a nacelle having an inlet, and wherein mass flow rates of media in proximity to the nacelle inlet correlate with the power levels and measuring the efficiency of engine operation, in order to aerodynamically control the operation of the engine through the range of operating stages, the present invention comprises an improvement comprising the step of adjusting nacelle inlet media flow separation with passive aerodynamic flow control, including flow ports in proximity to the nacelle inlet, which step of adjusting nacelle inlet media flow separation with passive aerodynamic flow control provides higher efficiency of engine operation than the efficiency of engine operation with a nacelle inlet without passive aerodynamic flow control as determined by power level.

In another exemplary embodiment, portions of the inlet to the entirety of the inlet is covered in rows of flow channels that connect the inside and outside surfaces of the inlet. The air moves along these channels because of the preexisting pressure difference. Portions of the numerous ports can be covered or otherwise blocked to allow for on-the-fly configurability of aerodynamic flow control (both as to number of available ports for aerodynamic flow, and the configuration(s) of those available ports.

The present aerodynamic flow control system enables variations of aerodynamic loads (e.g., the lift or side forces, pitching and yawing moments) and so it offers the potential for supplementing or, in some cases, replacing conventional aerodynamic control surfaces of aircraft or rotorcraft, or to enable enhanced control authority on moving bodies such as wind turbine blades or automotive vehicles. Controllable interactions of the aerodynamic flow and external flows can lead not only to changes in the global aerodynamic loads, but also to the development of structural materials that derive their functionality from controllable interactions with the flow over the body such that their mechanical properties are adaptively tailored by exploiting the aerodynamic flow-controllable distributions of the aerodynamic loads. The aerodynamic flow can fundamentally alter the effective stiffness, structural coupling, and damping properties of the structure and thus provides the ability to mitigate or completely avoid vibrations and aeroelastic instabilities.

In order to evaluate the beneficial characteristics of the present invention, the flow within an inlet of an engine nacelle model was investigated experimentally in the presence of crosswind with specific emphasis on separation over the windward inlet lip. The inlet flow is characterized using arrays of surface static pressure ports and radial total pressure rakes, surface oil-flow visualization, and limited particle image velocimetry (PIV).

The evolution of the flow topology over the windward lip surface was characterized over a range of crosswind speeds and inlet Mach numbers up to 35 knots and 0.8, respectively. It was found that the presence of sufficiently high crosswind relative to the inlet speed leads to the formation of a three-dimensional separation domain on the lip's inner surface. The separation domain has an azimuthal, horseshoe-like boundary with its tip near the windward edge – nominally $0.035D$ downstream of the lip's apex.

For a given inlet speed, the azimuthal position of the separation domain is affected by the inclination of the nacelle's inlet plane and the magnitude of the crosswind. As the crosswind speed increases, secondary interacting azimuthal separation cells whose topology resembles the main separation domain are triggered.

The use of the present innovative flow control, specifically passively enabling air flow between the outer and inner surfaces of the nacelle, mitigated of the separation. The present aerodynamic flow control leads to a reduction in cross stream total pressure deficit and concomitantly to a 3% increase in the inlet's mass flow rate (at a fixed operating point) at crosswind speeds of 30 to 35 knots.

In an exemplary embodiment, the present invention is an airflow control system comprising an aircraft engine, a nacelle for the aircraft engine, the nacelle open at an inlet lip and extending rearward from the lip with a windward outer surface and an inner surface, and an inlet flow separation abatement arrangement having an operational condition providing inlet flow separation abatement, wherein the nacelle inlet lip is configured to experience an inlet flow therethrough, wherein the physical geometries of the nacelle inlet lip leads to a range of uncontrollable inlet flow separation in proximity to the inlet lip during aircraft engine operation when the inlet flow separation abatement arrangement is not in the operational condition, wherein the inlet flow separation abatement arrangement, when in the operational condition, leads to a range of controllable inlet flow separation in proximity to the inlet lip during aircraft engine operation, and wherein the amount of uncontrollable inlet flow separation is greater than the amount of controllable inlet flow separation.

The inlet flow separation abatement arrangement can comprise an aerodynamic flow arrangement of ports in the windward outer and inner surfaces of the nacelle in proximity to the inlet lip, the aerodynamic flow arrangement configured to allow passive aerodynamic flow through the ports from a high pressure to a lower pressure.

The inlet flow separation abatement arrangement can comprise an aerodynamic flow arrangement of ports in the windward outer and inner surfaces of the nacelle in proximity to the inlet lip, the aerodynamic flow arrangement configured to allow passive aerodynamic flow through the ports from the windward outer surface to the inner surface.

5 When the inlet flow separation abatement arrangement is not in the operational condition, a virtual geometry of the nacelle inlet lip comprises only the physical geometries of the nacelle inlet lip, leading to the uncontrollable inlet flow separation in proximity to the inlet lip during aircraft engine operation, and wherein when the inlet flow separation abatement arrangement is in the operational condition, the virtual geometry of the nacelle
10 inlet lip comprises an alteration of the physical geometries of the nacelle inlet lip, leading to the controllable inlet flow separation in proximity to the inlet lip during aircraft engine operation.

Power to the aircraft engine during uncontrollable inlet flow separation presents a range of uncontrollable mass flow rates in proximity to the nacelle inlet lip, wherein the same
15 power to the aircraft engine during controllable inlet flow separation presents a range of controllable mass flow rates in proximity to the nacelle inlet lip, and wherein the controllable mass flow rates are at least 103% of the uncontrollable mass flow rates.

In another exemplary embodiment, the present invention is a nacelle for a gas turbine engine system comprising a housing having an inlet and an exhaust, and a pressure windward
20 outer surface and a suction inner surface, and an aerodynamic flow arrangement of ports in the pressure windward outer and suction inner surfaces of the housing in proximity to the inlet, the aerodynamic flow arrangement configured to allow passive aerodynamic flow through the ports from the pressure windward outer surface to the suction inner surface.

In another exemplary embodiment, the present invention is a gas turbine engine
25 comprising a nacelle defining an interior space, a fan section, a compressor section and a turbine section positioned within the nacelle, an inner cowl surrounding the compressor section and the turbine section, and the fan section delivering air to the compressor section, and flow control for selectively controlling the range of the flow of air through an aerodynamic flow arrangement of ports in the nacelle and upstream the fan section, the ports
30 extending from outside the nacelle into the interior space of the nacelle.

In another exemplary embodiment, the present invention is a method of aerodynamic control through media including operating an engine at power levels through a range of

operating stages, wherein the engine is within a nacelle having an inlet, and wherein mass flow rates of media in proximity to the nacelle inlet correlate with the power levels, and measuring the efficiency of engine operation, in order to aerodynamically control the operation of the engine through the range of operating stages, the present invention being an improvement comprising the step of adjusting nacelle inlet media flow separation with passive aerodynamic flow control, including flow ports in proximity to the nacelle inlet, which step of adjusting nacelle inlet media flow separation with passive aerodynamic flow control provides higher efficiency of engine operation than the efficiency of engine operation with a nacelle inlet without passive aerodynamic flow control as determined by power level.

The operating stages can be selected from the group consisting of taxi, takeoff, climb, cruise, descent and landing.

Adjusting nacelle inlet media flow separation with passive aerodynamic flow control can provide at least 3% higher efficiency of engine operation than the efficiency of engine operation with a nacelle inlet without passive aerodynamic flow control. Adjusting nacelle inlet media flow separation with passive aerodynamic flow control can provide at least 6% higher efficiency of engine operation than the efficiency of engine operation with a nacelle inlet without passive aerodynamic flow control. Adjusting nacelle inlet media flow separation with passive aerodynamic flow control can provide at least 10% higher efficiency of engine operation than the efficiency of engine operation with a nacelle inlet without passive aerodynamic flow control.

Thus, as examples only, and not meaning to be bound by any specific combination of inventive features, the present invention includes many exemplary embodiments that are created by a combination of various different features.

These and other objects, features and advantages of the present invention will become more apparent upon reading the following specification in conjunction with the accompanying drawing figures.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a side view of an aircraft nacelle with an aerodynamic flow control system according to an exemplary embodiment of the present invention.

FIG. 2 illustrates a nacelle inlet with arrays of flow ports between the external and internal surfaces around its circumference according to an exemplary embodiment of the present invention.

FIG. 3 is a cross section perspective view of a portion of the nacelle inlet of **FIG. 2**.

FIG. 4 is another cross-section perspective view of a portion of the nacelle inlet of **FIG. 2**, showing internal air passages (or flow paths) with schematic representation of actuation valves according to an exemplary embodiment of the present invention.

5 **FIG. 5** are schematic renditions of flow control in proximity to the nacelle inlet of the present invention: the separated flow in the absence of flow control (**FIG. 5A**), flow attached using the inventive flow control (**FIG. 5B**), the “virtual” change in nacelle thickness enabled by the inventive flow control (**FIG. 5C**).

10 **FIG. 6** presents surface oil-flow visualization about the nacelle lip (**FIG. 6A**) and a raster plot of the mean vorticity ζ with overlaid mean velocity vector field (**FIG. 6B**) for the inlet mass flow rate $\dot{m}^* = 0.99$ and no crosswind. Schematics of inlet surface are shown for reference.

FIG. 7 illustrates total pressure rake and static port ($\square$) azimuthal orientation (**FIG. 7A**) and the dashed horizontal PIV field of view (**FIG. 7B**).

15 **FIG. 8** presents total pressure profiles at eight azimuthal orientations $\theta = 0^\circ$ (**FIG. 8A**), 45° (**FIG. 8B**), 90° (**FIG. 8C**), 135° (**FIG. 8D**), 180° (**FIG. 8E**), 225° (**FIG. 8F**), 270° (**FIG. 8G**), and 315° (**FIG. 8H**) and for four mass flow rates $\dot{m}^* = 0.78$ ($\square$), 0.86 ($\triangle$), 0.98 ($\circ$), and 0.99 ($\times$).

20 **FIG. 9** shows surface oil visualization with $U_0 = 35$ knots crossflow at $\dot{m}^* = 0.74$ (**FIG. 9A**), 0.79 (**FIG. 9B**), 0.94 (**FIG. 9C**), and 0.98 (**FIG. 9D**).

FIG. 10 presents total pressure profiles at eight azimuthal orientations $\theta = 0^\circ$ (**FIG. 10A**), 45° (**FIG. 10B**), 90° (**FIG. 10C**), 135° (**FIG. 10D**), 180° (**FIG. 10E**), 225° (**FIG. 10F**), 270° (**FIG. 10G**), and 315° (**FIG. 10H**) for $U_0 = 35$ knots crosswind and four mass flow rates $\dot{m}^* = 0.74$ ($\square$), 0.79 ($\triangle$), 0.94 ($\circ$), and 0.98 ($\times$).

25 **FIG. 11** shows surface oil visualization for fixed mass flow rate at crosswind speeds of 25 (**FIG. 11A**), 30 (**FIG. 11B**), and 35 knots (**FIG. 11C**), and the total pressure profiles corresponding to these cases at three azimuthal locations $\theta = 225^\circ$ (**FIG. 11D**), 270° (**FIG. 11E**), 315° (**FIG. 11F**) for the crosswind speeds $U_0 = 0$ ($\square$), 25 ($\triangle$), 30 ($\circ$), and 35 ($\times$) knots.

30 **FIG. 12** presents total pressure profiles at six azimuthal orientations $\theta = 90^\circ$ (**FIG. 12A**), 210° (**FIG. 12B**), 240° (**FIG. 12C**), 270° (**FIG. 12D**), 300° (**FIG. 12E**), and 330°

(**FIG. 12F**) for inlet mass flow rate $\dot{m}^* \approx 0.74$ at crosswind speeds $U_0 = 0$ ($\square$), 25 ($\triangle$), 30 ($\circ$), and 35 ($\times$) knots.

FIG. 13 is a graph of inlet mass flow rate $\dot{m}^*$ with blower power for the crosswind speed $U_0 = 0$ ($\square$), 25 ($\triangle$), 30 ($\circ$), and 35 ($\times$) knots.

5 **FIG. 14** illustrates the effects of crosswind on the flow about an engine nacelle in ground operation, namely separation (**FIG. 14A**), internal separation in proximity to the nacelle inlet (**FIG. 14B**), and the formation of a ground vortex (**FIG. 14C**).

FIG. 15 shows nacelle inlet mass flow rate with three configurations of clusters of flow ports: flow from top ($\square$), bottom ($\triangle$), and middle ($\circ$) on the windward side of the inlet at crosswind of 50 knots.

FIG. 16 presents total pressure profiles at three azimuthal orientations $\theta = 225^\circ$ (**FIGS. 16A, D**), 270° (**FIGS. 16B, E**), and 315° (**FIGS. 16C, F**) at two crosswind speeds $U_0 = 30$ (**FIGS. 16A-C**) and 35 (**FIGS. 16D-F**) knots for the uncontrollable ($\square$) and controllable ($\triangle$) flow.

15 **FIG. 17** presents total pressure profiles at three azimuthal orientations $\theta = 225^\circ$ (**FIGS. 17A, D**), 270° (**FIGS. 17B, E**), and 315° (**FIGS. 17C, F**) at two crosswind speeds $U_0 = 30$ (**FIGS. 17A-C**) and 35 (**FIGS. 17D-F**) knots for the uncontrollable ($\square$) and controllable ($\triangle$) flow.

FIG. 18 illustrates ramped inlet flow at fixed crossflow: $U_0 = 35$ knots for one configuration of flow ports.

FIG. 19 illustrates a normal projection of **FIG. 18**.

FIG. 20 presents total pressure profiles at three azimuthal orientations $\theta = 225^\circ$ (**FIGS. 20A, D**), 270° (**FIGS. 20B, E**), and 315° (**FIGS. 20C, F**) at two crosswind speeds $U_0 = 30$ (**FIGS. 20A-C**) and 35 (**FIGS. 20D-F**) for the uncontrollable ($\square$) and controllable ($\triangle$) flow.

FIG. 21 illustrates ramped inlet flow at fixed crossflow: $U_0 = 30$ knots for another configuration of flow ports.

DETAIL DESCRIPTION OF THE INVENTION

To facilitate an understanding of the principles and features of the various embodiments of the invention, various illustrative embodiments are explained below.

Although exemplary embodiments of the invention are explained in detail, it is to be understood that other embodiments are contemplated. Accordingly, it is not intended that the invention is limited in its scope to the details of construction and arrangement of components set forth in the following description or illustrated in the drawings. The invention is capable
5 of other embodiments and of being practiced or carried out in various ways. Also, in describing the exemplary embodiments, specific terminology will be resorted to for the sake of clarity.

It must also be noted that, as used in the specification and the appended claims, the singular forms “a,” “an” and “the” include plural references unless the context clearly dictates
10 otherwise. For example, reference to a component is intended also to include composition of a plurality of components. References to a composition containing “a” constituent is intended to include other constituents in addition to the one named.

Also, in describing the exemplary embodiments, terminology will be resorted to for the sake of clarity. It is intended that each term contemplates its broadest meaning as
15 understood by those skilled in the art and includes all technical equivalents which operate in a similar manner to accomplish a similar purpose.

Ranges may be expressed herein as from “about” or “approximately” or ‘substantially’ one particular value and/or to “about” or “approximately” or ‘substantially’ another particular value. When such a range is expressed, other exemplary embodiments
20 include from the one particular value and/or to the other particular value.

Similarly, as used herein, ‘substantially free’ of something, or ‘substantially pure’, and like characterizations, can include both being “at least substantially free” of something, or “at least substantially pure”, and being “completely free” of something, or “completely pure”.

By “comprising” or “containing” or “including” is meant that at least the named
25 compound, element, particle, or method step is present in the composition or article or method, but does not exclude the presence of other compounds, materials, particles, method steps, even if the other such compounds, material, particles, method steps have the same function as what is named.

It is also to be understood that the mention of one or more method steps does not
30 preclude the presence of additional method steps or intervening method steps between those steps expressly identified. Similarly, it is also to be understood that the mention of one or

more components in a composition does not preclude the presence of additional components than those expressly identified.

The materials described as making up the various elements of the invention are intended to be illustrative and not restrictive. Many suitable materials that would perform the same or a similar function as the materials described herein are intended to be embraced
5 within the scope of the invention. Such other materials not described herein can include, but are not limited to, for example, materials that are developed after the time of the development of the invention.

Generally, the present invention concerns systems and methods for intelligent
10 regulation and control of a distributed fluid flow. The present invention discloses flow control and stabilization capabilities of distributed flow actuation.

When a fluid is in motion over a surface of a structure, the moving fluid or a crossflow causes a pressure distribution over the surface. Depending on the shape of the structure, local pressure of a certain region of the surface varies. The difference in the
15 pressure distribution over the surface causes global aerodynamic or hydrodynamic forces and moments, such as lift, drag, pitching moment. Aerodynamic flow is initiated when there is a flow circulation through the surface from high pressure to low pressure.

Traditionally, forces and moments around the structure in crossflow are altered or controllable by introducing a hard control surface to interact with the crossflow. The
20 aerodynamic flow, once actuated, interacts with the crossflow without introducing a hard control surface to the crossflow about the structure. Therefore, the aerodynamic flow eliminates many restrictions and limits that a traditional hard control surface imposes with regard to the design of a structure, such as an aircraft.

Passive aerodynamic flow refers to aerodynamic flow that is invariant with time. The
25 passive aerodynamic flow cannot be altered or regulated, and as such changes in parameters of fluid such as pressure cannot be altered or regulated. On the contrary, regulating an aerodynamic flow that interacts with the crossflow enables modification of parameters of fluid over the structure which leads to control of aerodynamic or hydrodynamic forces and moments of the structure. The present invention discloses a system and method of regulating
30 and controlling aerodynamic flow to modify various forces and moments in a crossflow over a structure exposed in a moving fluid.

The structure contemplated herein may be any structure of any material that is being

placed in any type of fluid. Examples of structures contemplated herein may include, but are not limited to, aerodynamic structures, such as a nacelle.

A distributed fluid flow system may comprise a structure with crossflow streaming around the structure. An aerodynamic flow passage may be formed through the structure providing a passage for the crossflow to enter into the structure, thereby forming an aerodynamic flow. The crossflow over the structure may initiate pressure differences across a surface of the structure (typically the outer surface), which enables the aerodynamic flow through the aerodynamic flow passage. The aerodynamic flow passage need not be limited to any size, shape, or form. The aerodynamic flow passage may be any type of through-way that provides a passage for the aerodynamic flow to pass through the structure.

In one embodiment, an aerodynamic flow inlet may be formed on a surface of the structure to receive the crossflow to enter through the aerodynamic flow passage. The aerodynamic flow inlet may be positioned at a high-pressure region of the crossflow about the structure.

In another embodiment, an aerodynamic flow outlet may be formed on a surface of the structure to release the received crossflow from the aerodynamic flow inlet through the aerodynamic flow passage, into a lower pressure region of the crossflow. The aerodynamic flow outlet may be positioned at the low-pressure region of the crossflow.

The aerodynamic flow introduced to the crossflow at the aerodynamic flow outlet may modify pressure and direction of the crossflow. Similarly, pressure and direction of the crossflow at the aerodynamic flow inlet also may be modified due to the aerodynamic flow being drawn from the crossflow. In both cases, the modification in pressure and flow around the structure may lead to alteration of pressure distribution, aerodynamic forces, hydrodynamic forces, vorticity, or moments about the structure.

In another embodiment, an aerodynamic flow outlet may be formed on a surface of the structure to release the received crossflow from the aerodynamic flow inlet through the aerodynamic flow passage, into a lower pressure region of the crossflow. The aerodynamic flow outlet may be positioned at the low-pressure region of the crossflow.

The aerodynamic flow introduced to the crossflow at the aerodynamic flow outlet may modify pressure and direction of the crossflow. Similarly, pressure and direction of the crossflow at the aerodynamic flow inlet also may be modified due to the aerodynamic flow being drawn from the crossflow. In both cases, the modification in pressure and flow around

the structure may lead to alteration of pressure distribution, aerodynamic forces, hydrodynamic forces, vorticity, or moments about the structure.

In a further embodiment, the aerodynamic flow may modify global forces about the structure and alter a virtual shape of the structure. The crossflow wraps around the structure and a streamline of the crossflow is defined by the shape of the structure. Once the
5 aerodynamic flow is introduced to the crossflow, the modification applied to pressure and direction of the crossflow about the structure may alter the streamline of the crossflow. A sink may be formed near the aerodynamic flow inlet where a suction force may alter the streamline. A source may be formed near the transported outlet where the streamline may be
10 pushed away from its original path before the aerodynamic flow is introduced.

Those of ordinary skill in the art will appreciate that the location and the number of the aerodynamic flow inlets and aerodynamic flow outlets may vary in order to make desired modification and alteration about the structure discussed above.

The structure may employ more than one of the aerodynamic flow passages to
15 introduce more than one aerodynamic flow to the crossflow. A plurality of aerodynamic flow inlets and aerodynamic flow outlets may be distributed over the surface of the structure to enable any desired modification and alteration of pressure distribution, aerodynamic forces, hydrodynamic forces, vorticity, or moments , of the crossflow about the structure.

In one embodiment, the aerodynamic flow may flow from a single aerodynamic flow
20 inlet and out to more than one aerodynamic flow outlet.

In another embodiment, the aerodynamic flow may flow from more than one aerodynamic flow inlet and out to a single aerodynamic flow outlet.

In yet another embodiment, a plurality of aerodynamic flows may be formed from a plurality of aerodynamic flow inlets to a plurality of aerodynamic flow outlets.

25 In a further embodiment, the plurality of aerodynamic flow inlets and aerodynamic flow outlets may be distributed over the surface of the structure in a span-wise direction.

The distributed fluid flow system may further comprise an actuation mechanism and an actuator. The actuation mechanism may be coupled to the aerodynamic flow inlet or outlet where the actuation mechanism allows the aerodynamic flow passage to be open or
30 closed. The actuator may be operatively coupled to the actuation mechanism to enable the actuation mechanism. By employing the actuation mechanism to selectively open or close

the aerodynamic flow inlet or outlet, the aerodynamic flow may be regulated in a time-dependent fashion.

In one embodiment, the aerodynamic flow inlet may be closed by the actuation mechanism, thereby preventing the aerodynamic flow from being introduced to the crossflow.

In another embodiment, the aerodynamic flow outlet may be closed by the actuation mechanism, thereby preventing the aerodynamic flow from being introduced to the crossflow.

In yet another embodiment, the actuator may enable the actuation mechanism to be at an open position, a closed position, or any other positions therebetween. When the actuation mechanism is at the any other position therebetween, the variation in opening of the actuation mechanism may adjust the flow rate of the aerodynamic flow which may affect modifying and altering the crossflow.

The actuation mechanism contemplated herein may be any mechanism that is capable of controlling the introduction of the aerodynamic flow to the crossflow.

The actuators contemplated herein may include, but are not limited to, mechanical, electromechanical, electromagnetic, thermal, chemical, piezoelectric, shape memory alloy, pneumatic, hydraulic actuators, balloons and the like. The actuators may be integrated into the surface of the structure or mounted within the structure.

Examples of the actuators and the actuation mechanisms may include, but are not limited to, mechanical means such as, linear rod-type actuators, sliding perforated plates, pneumatic actuators, inflatable or deformable bladders, etc. that open and close ports in the structure's surface with sufficient time-response to enable aerodynamic flow. Electromechanical actuators including, piezoelectric surfaces, reeds, linear drives, or stacks that generate mechanical force and displacement under applied voltage, electrostatic materials that deform in one or multiple dimensions in response to applied voltage, or otherwise "smart" materials or structures that operate with electric current to actuate. Similarly, electromagnets, which induce a magnetic field in response to an applied voltage, may or may not be combined with permanent magnets to control surface openings. Thermal actuators, such as shape memory alloy materials, such as, planar sheets or wires, or laminated metal, such as, clad or bimetal strips, which deform in a controllable manner in response to temperature differences which may be generated by electric current, may also be used as

mechanisms to regulate aerodynamic flow inlets and aerodynamic flow outlets. Chemical actuators, similarly, can be designed to react in a controllable fashion to generate mechanical force, heat, or electric current or could be combined with the above methods to produce surface deflections or openings.

5 The distributed fluid flow system may further comprise an aerodynamic flow control system operatively coupled to the actuator which regulates operation of the actuator.

After characterization of the engine inlet flow at the varying mass flow rates and crosswind speeds, the question is what can be done to alleviate some of the detrimental effects of the crosswind, predominantly expressed in terms of the total pressure losses (and
10 the mass flow reduction) and distortions. The present flow control approach, by the existing high-pressure differential between the outer windward nacelle, having the high stagnation pressure, and the inner surface of the inlet lip, creating a high-pressure differential, prompted an application of autonomous aerodynamic flow.

The present invention relates to an aerodynamic flow system for a nacelle inlet, which
15 experiences separation on its windward side if in a strong enough crosswind. This separation is complex and changes in shape, azimuthal extent, radial extent, and complexity. By opening up a flow port, air will move naturally along the pressure gradient from the outside of the nacelle to the inside.

Inlet and outlet ports can be all located in proximity to the nacelle inlet. In such an
20 embodiment, the outer surface of the nacelle will virtually always be at a higher pressure than within the nacelle, and thus fluid flow will be from outside the nacelle to inside the nacelle when the present invention is activated.

In another embodiment of the present invention, inlet and/or outlet ports can be located in the nacelle or housing downstream the fan and/or compressor and/or the turbine,
25 where such rear-located ports enable fluid flow from inside the housing to outside the housing.

As such, the present invention is capable of adjusting the virtual shape of either or both the inside and outside of the housing. Further, intelligent control of the flow path(s) provided by the present invention can also take into account the flow
30 disturbances/characteristics presented by other elements of the airplane, like the pylons. Although the air flow control of the present invention may not locate ports in/on such additional structures like the pylons, measurements of flow at nacelle inlet, nacelle outlet,

pylons, and wing surfaces, among others, might affect how the ports are configured to provide an overall more efficient system. Not one just based on nacelle inlet conditions.

Air will be drawn into the inlet along these ports, and this flow will move along the inner wall creating a new “virtual surface” (see, **FIG. 5C**). Looking at the separation from the baseline cases (namely the oil flow in **FIGS. 2** and **12**), one can see where the flow separates, which also indicates the areas where the preexisting wall is not conducive to flow attachment at this condition of crosswind speed and intake speed.

By carefully selecting which flow ports are open (chosen from the observed separation in the baseline cases) the inner surface of the inlet “changes” in these areas. This new surface can be more resistant to separation since the wall is now “thicker” in these areas allowing the crossflow to better manage the turn into the inlet.

This can then lead to the flow remaining attached to this new surface, leading to a decrease in the total pressure losses and an increase in the mass flow rate. These flow ports could be opened/closed dynamically using actuators in order to provide the optimal aerodynamic flow control/virtual surface for a given crosswind/mass flow rate.

As the engine ramps up, the optimal aerodynamic flow configuration would likely change since it was observed that the flow topology changes significantly (**FIG. 9**). Thus, judiciously choosing aerodynamic flow configurations leads to observed total pressure losses that can be significantly reduced while more mass flow (i.e. thrust) can be produced for an equivalent level of engine power.

A nacelle **100** is shown in **FIG. 1**. As an example, a nacelle **100** typically encloses an engine and is positioned externally of the engine that powers the aircraft to which it is coupled. The annular nacelle **100** (e.g., an outer housing or cowling) extends circumferentially about the gas turbine engine. A gas turbine engine generally includes in serial flow relationship a fan **130**, a compressor, a combustion section, and a turbine section. Air compressed in the compressor is mixed with fuel that is burned in the combustion section and expanded in turbine section. The air compressed in the compressor and the fuel mixture expanded in the turbine section can both be referred to as a hot gas stream flow. The turbine section can include rotors that, in response to the expansion, rotate to drive the fan and compressor.

The nacelle **100**, as shown, can itself be generally divided into sections, including from inlet to exhaust - an inlet section **120**, a fan cowl section, a thrust reverser section, and

an exhaust section. In the present invention, the inlet section **120** comprises an aerodynamic flow control system **200**.

The aerodynamic (or hydrodynamic) loads on bluff and lifting bodies like jet engines in an ambient media (for example, gas or liquid) crossflow can be manipulated by interactions between the crossflow over the surface or skin of the nacelle **100**, and distributed aerodynamic flow of the ambient media that is directed through arrays of flow ports or orifices **210** in/through the skin of the nacelle **100**.

The surface of the nacelle **100** includes a number of ports **210** that are open to an inner volume within the nacelle **100**, and aerodynamic flow between open ports is driven by pressure differences (from high to low pressure) that are determined by the external flow over the nacelle **100**. As flow through the aerodynamic flow control system **200** is, as defined, passive, the aerodynamic flow is driven only by pressure differences from high to low.

The ports **210** can be located anywhere along the surface, both upstream and downstream the fan depending on control schemes, and 360° around the housing (or any portion thereof). Port location determines flow path (can be from outside the housing to inside the housing, or if ports are located in high pressure zones of the engine system, from inside the housing to outside the housing), flow direction, and flow amount, just to name a few specifications. Ports located on the bottom portion of a housing would support same ground operation of the engine (limiting vortexes that can sweep runway debris into the engine), and those ports intelligently located at other areas about the housing providing similar benefits in different situations.

The interaction between the aerodynamic flow and external flows are designed to form “virtual” changes in the aerodynamic shape of the nacelle **100** by engendering concentrations of trapped vorticity and/or streamwise vorticity that lead to alteration of the nacelle’s apparent aerodynamic shape (for example, local change in camber), and thereby in the local aerodynamic loads on the structure. The aerodynamic flow modifies global forces about the nacelle and alter a virtual shape of the nacelle. The crossflow wraps around the nacelle and a streamline of the crossflow is defined by the shape of the nacelle. Once the aerodynamic flow is introduced to the crossflow, the modification applied to pressure and direction of the crossflow about the nacelle alters the streamline of the crossflow. A sink may be formed near the aerodynamic flow inlet where a suction force may alter the streamline. A source may be formed near the transported outlet where the streamline may be

pushed away from its original path before the aerodynamic flow is introduced.

As shown in **FIGS. 2-3**, in an exemplary embodiment, the inventive aerodynamic flow regulation system includes inlets and outlets in the inlet section **120** of the nacelle **100** that are each in communication with one another because each defines a port **210** into/out of a
5 common volume within the nacelle, the entirety of which is available to all. In this embodiment, the present invention does not dictate flow path to the extent that only certain ports can possibly fluidly communicate since they are located in a path or passage through the nacelle. The entirety of the inner volume available to the ports is available to all ports.

In such an innovative design, where each port is, individually, communicative with
10 the same internal volume (the whole of the available volume), each port actually has dual functionality (i.e., it can act as an “inlet” or “outlet”) depending on the pressure distribution over the surface of the body (which can change with the flow of the ambient media). So that the functionality of the ports is reconfigurable and can be changed by opening or closing selected ports, and/or by changes in the external pressure distribution. As a result, the
15 direction of the aerodynamic flow through the ports depends on the motion of the airfoil and can be reversed or stopped.

In another exemplary embodiment, the inventive aerodynamic flow regulation system includes inlets and outlets in the inlet section **120** of the nacelle **100** that define individual flow paths for aerodynamic flow, wherein a pair of ports, and inlet and an outlet, do not
20 communicate with any other flow path.

In yet another exemplary embodiment, the inventive aerodynamic flow regulation system includes inlets and outlets in the inlet section **120** of the nacelle **100** that define both a first set of inlets and outlets that are each in communication with one another because each defines a port **210** into/out of a common volume within the nacelle, the entirety of which is
25 available to all, and a second set of inlets and outlets that define a number of exclusive flow paths between single inlets and outlets.

As noted in an exemplary embodiment, the aerodynamic flow between high- and low-pressure domains on the surface of the nacelle occurs through an internally-connecting volume (or internal plenum chamber) that is formed and, in most instances, fully bounded by
30 the external surface (shell or skin) of the nacelle. The aerodynamic flow rate into and out of the surface ports/orifices depends on the available pressure differences over the surface and the flow resistance through the surface orifices and through flow passages within the volume.

The choice of port/orifice size, planform shape and scale, their characteristic dimensions (including depth), and their distribution on the surface of the nacelle's skin depends on the available driving pressure distribution over the surface of the nacelle that depends on the speed of the embedding flow (or the speed of the nacelle) and on the nacelle's scale.

The flow through the surface orifices through the present aerodynamic flow control can be easily reconfigured as the flight (or motion) conditions of the nacelle change as long as there is a pressure difference between these domains (or between these domains and the internal pressure within the volume).

The aerodynamic flow in and out of the surface of the nacelle can be regulated either passively by prescribing a desired distribution of orifices and by varying their cross-sectional area (or planform shape), or by using local valving for throttling of the flow. One example of such surface throttling are distributed actuation valves **220** as shown in **FIG. 4**.

The general inventive approach of the present invention is shown in **FIG. 5**. In **FIG. 5A**, the flow **310** in the inlet of nacelle **100** is shown notionally, where the flow **310** is separated over the inner surface of the nacelle inlet and forms a separation bubble **320**. Actuation on the inner surface using the present aerodynamic flow control system leads to local attachment of the flow (**FIG. 5B**), and therefore the effects of the actuation may be thought of as a "virtual" change in the surface contour or mold line (**FIG. 5C**) that would be associated with the imposed change in the streamwise pressure gradient (virtual surface contour **150**).

In the present invention, the actuation is provided by an innovative approach to aerodynamic control using distributed, scalable autonomous air aerodynamic flow actuation on a conventional nacelle inlet **120**. The aerodynamic flow is driven through the nacelle's aerodynamic surfaces (**FIG. 2**) by the inherent pressure differences between the inner and outer surfaces of the nacelle when the engine is operating.

The aerodynamic flow can be autonomous or regulated by low-power, surface-integrated louver valves **220** (e.g., piezoelectric) as depicted notionally in **FIG. 4**. Interaction between controllable aerodynamic flow and the crossflow can be tailored to leverage the generation and regulation of vorticity concentrations on or near the surface to locally alter its apparent aerodynamic shape and therefore the flow direction and aerodynamic loads. Aerodynamic flow actuation which is driven solely by local pressure differences across the

airframe, does not require powered air source, is easily airframe integrable and scalable in low-observable fashion, and can be used to mitigate separation in complex wind gusts during taxiing, takeoff, and landing. The notional flow ports **210** can cover any part of the circumference of the nacelle inlet **120** and the valves **220** can be implemented at one or both ends.

Experiments

The effectiveness of aerodynamic flow actuation on the flow around a (nominally 6% scale) nacelle inlet model has been demonstrated in the presence of relevant crosswind conditions in laboratory experiments at Georgia Tech using a controllable blower operated in suction as a surrogate model of the engine plant.

The variation of the mass flow rate through the nacelle ($\dot{m}$) with blower suction was characterized by varying the blower power P_B (where the maximum blower power is $P_{B,max}$). The mass flow rate through an experimentally nacelle configuration was normalized by the choked (or critical) mass flow rate $\dot{m}_c$. These data show that following an initial sharp increase, $\dot{m}$ tapers with increasing blower power until it asymptotes to $\dot{m}_c$ at just over half of the maximum available blower power and remains unchanged thereafter. Consequently, the facility is well equipped to achieve the maximum possible $\dot{m}$ through this a nacelle model.

An illustration of the flow drawn into the inlet in the absence of the crosswind is shown in **FIG. 6** in order to use it as a basis for comparison. **FIG. 6A** shows surface oil flow visualization on the wall. The axially aligned streaks in the flow show that the flow is uniformly drawn in from all directions, as would be expected in the absence of the crossflow. **FIG. 6B** shows particle image velocimetry (PIV). The velocity vectors indicate that the flow is able to properly manage the turn into the inlet without separating off the wall. Only losses are attributed to the boundary layer at the wall.

As shown, short strips of tape (approximately $0.074D$ long, 4.6 thousands thick) were used to trip the flow over the inlet lip. Similar tape was used to cover the static pressure ports during the surface oil visualization. Oil flow visualization images of the corresponding flow field about the leading inlet lip are shown in **FIGS. 6A, B** respectively for $\dot{m}^* = \dot{m}/\dot{m}_c = .99$.

The visualization over the windward azimuthal span ($180^\circ < \theta < 360^\circ$) indicates that the flow turns smoothly and is nearly-uniformly drawn into the inlet – as would be expected in the absence of the crosswind. For reference, the azimuthal positions of the visible total

pressure rakes are labeled on the image. This topological feature is supported by PIV measurements in the central horizontal plane $\theta = 270^\circ$, as shown in **FIG. 6B** by a raster plot of the azimuthal vorticity superposed with mean velocity vectors (the image also includes the inlet surface for reference). These data also demonstrate that the surface boundary layer thickens as the inlet flow turns and accelerates around the lip, and that the boundary layer thins as the flow accelerates into the inlet while the core flow aligns with the inlet axis.

A nacelle model used to test a broad range of inlet section configurations was mounted on a flow duct that is driven in suction by a dedicated, computer-controllable blower. The nacelle model, which has a throat inlet diameter D , was attached to a diffuser followed by a long straight duct segment upstream of the blower's inlet. The duct was equipped with a probe for mass flow rate measurements placed between two flow straighteners both upstream and downstream.

The blower exhaust air was driven into the room through two chilled water heat exchangers so that the ambient air temperature in the room is maintained at a prescribed level to within 1°C . The nacelle-duct assembly and the blower were supported on a movable frame with casters that enabled angular, α , and axial adjustability about a pivot at the center of the crossflow test section, thereby allowing for adjustment of the nacelle's centerline relative to the crosswind and of the protrusion of the nacelle's inlet into the test section.

The crossflow was generated by an open-return, low-speed wind tunnel having a contraction ratio of 10:1 and is driven by a computer-controllable axial blower. The tunnel's square test section (107 cm on the side) was optically transparent from three sides to enable measurements of the flow field about the nacelle's inlet using PIV and flow visualization. The uniformity of the air speed within the test section was verified using velocity measurements at various locations of its exit plane.

As shown in **FIG. 7A**, total pressure rake is able to measure total pressure losses in 45° increments (0° , 45° , 90° , 135° , 180° , 225° , 270° and 315°). There are also static wall ports primarily located on the windward side (squares). **FIG. 7B** shows the PIV field of interest, which is located at the horizontal central plane (270°) so that the flow can be seen as it manages the turn into the inlet.

The nacelle inlet flow was characterized using eight radial rakes of total pressure probes that are distributed azimuthally at 45° increments around the perimeter just upstream of the duct's throat. The number of ports alternated between 10 and eight inches long and

short segments as shown schematically in **FIG. 7A** (there are also static pressure ports at the surface next to each rake). In addition, the nacelle inlet was also equipped with eight streamwise rows of static pressure ports along the nacelle's inlet surface that are marked by square symbols in **FIG. 7A**. The pressure distributions were measured using a dedicated 96-
 5 channel pressure scanner (uncertainty better than 1%).

Detailed flow features on the inner surface of the inlet were explored using oil-flow visualization. Oil was placed on the windward side of the nacelle at multiple axial positions between the lip and the total pressure rakes. The inlet flow was also characterized using planar PIV using a LaVision system. **FIG. 7B** illustrates an example of a PIV field of view
 10 where the laser sheet intersects the windward lip of the nacelle and the field of view is marked by a dashed rectangle. The CMOS camera ($2,560 \times 2,160$ pixels) is mounted on a traverse above the test section and is angled to capture a segment of the flow into the inlet.

Radial distributions of normalized total pressure $p^* = (p_o - p_a)/p_a$ at the eight azimuthal rake positions (**FIG. 7A**) measured for four inlet mass flow rates ($\dot{m}^* = 0.78, 0.86, 0.98, \text{ and } 0.99$) in the absence of crosswind, are shown in **FIG. 8**. **FIG. 8** shows the total pressure profiles corresponding to the inlet flow without a crosswind. Different shades indicate different intake speeds. The overlapping of the profiles indicates no losses. Where the profiles do not overlap (at low values of y/R (i.e., close to the wall)), there are more losses. In this case, the losses are from the growing boundary layer at the wall.

Within the resolution of the measurements, these distributions exhibit no evidence of separation due to flow turning around the nacelle lip and little variation for the different mass flow rates within the core flow. Furthermore, as expected, the total pressure deficit is only measured in the near-wall region due to the boundary layer and increases with the inlet mass flow rate. Overall, the total pressure distributions suggest that, in the absence of crosswind,
 20 the inflow is rather smooth with minimal losses.

In a first introduction of crosswind, **FIG. 9** presents an array of crosswind cases - increasing crosswind and increasing intake speed. Shown here is what happens to the flow as the intake speed is increased for a fixed crosswind speed (35 knots). Clearly, in doing so, the main separation moves azimuthally upwards while the separation gains significant complexity.
 30

As the PIV captures only a single horizontal cut of the flow field, more insight into the flow separation topology is sought through the surface oil-flow visualization of the inlet

windward side. Four such realizations are shown for the crosswind speed fixed at 35 knots, for the increasing inlet mass flow rate. Some of the salient features of the topology are accentuated by the schematics. First, the main separation domain is marked by the dashed line. At the lowest mass flow rate, this region is azimuthally displaced below the horizontal plane (270°). Moreover, it is bound by the two circulating cells on its upper and lower azimuthal bounds, as marked schematically. The flow departure from axially aligned relaxes away from this main separation region, such that it reverts back to being axially aligned towards the bottom (180°) and top (330°), as emphasized by the arrows.

As the flow rate is slightly increased (point to the second one), only a slight modification of the separation topology is seen, mostly indicating a stronger pattern of the bounding cells. However, as the flow rate is increased steeper, the separated domain appears to both shrink in size and becomes displaced azimuthally upward. Aside from this main effect, there is an increased complexity in the separation topology, as additional small separation cells begin to form about the inlet lip (point to $\dot{m}^* = 0.94$). At the highest flow rate, there appears to be a secondary separation domain centered at about 230°, while the main domain is pushed to 270°.

The presence of crosswind exacerbates the inlet flow significantly and can lead to separation on the windward side of the inner surface. Oil visualization images of the complex topology of the ensuing flow on an azimuthal segment of the inlet inner surface at a fixed crosswind speed of 35 knots and four inlet mass flow rates $\dot{m}^* = 0.74, 0.79, 0.94$, and 0.98 are shown in **FIG. 9**. In addition to separation, which is observed for all cases, the oil-flow traces clearly indicate the growing complexity of the flow topology with the increasing $\dot{m}^*$.

The simplest separation topology occurs at $\dot{m}^* = 0.74$ (**FIG. 9A**), where a clear separation domain is marked by a horseshoe-like boundary whose narrow leading edge is centered at about $\theta = 235^\circ$ – well below the horizontal center plane. As the separation pattern spreads azimuthally in the downstream direction, it approximately covers the domain $205^\circ < \theta < 265^\circ$ just upstream from the total pressure rakes. Besides this main flow separation feature, the flow drawn into the inlet exhibits clear angularity on either side of the separated domain.

The angularity of the inlet flow below $\theta = 235^\circ$ gradually relaxes, such that the flow between $\theta = 180^\circ$ and about 205° is drawn axially into the inlet as it would in the absence of

the crossflow. The incoming flow angularity is even more pronounced above the separation domain. A strong curving outside the separation boundary is seen up to about $\theta = 315^\circ$, with evidence of a possible circulating cell on the outer upper boundary centered at about $\theta = 265^\circ$. At the lower- and upper-most azimuthal extents, the flow angularity relaxes, and the flow is drawn axially into the inlet over the ranges $180^\circ < \theta < 210^\circ$ and $330^\circ < \theta < 360^\circ$. As the inlet mass flow rate is increased to $\dot{m}^* = 0.79$ (**FIG. 9B**), no significant changes in the topology are observed, although most of the features become better defined in the oil traces.

First, the leading-edge flow separation somewhat widens and slightly shifts upward azimuthally, now centered at about $\theta = 240^\circ$. Second, the circulating cell on the upper boundary of the separated region is fully traced, having a focus at about $\theta = 260^\circ$. Furthermore, the lower boundary of the separated region depicts an elongated turning line of the flow. Neither of these features is clearly seen in **FIG. 9A**, which might also be attributed to the insufficient shear to oil viscosity ratio in that section of the surface.

It is interesting that the overall azimuthal spread of the separated domain remains approximately unchanged in front of the total pressure rakes but is azimuthally offset to $210^\circ < \theta < 270^\circ$. Although the lower inlet flow straightens into the inlet at higher azimuthal angles, when compared to the lowest mass flow rate (see the lesser angularity of the lower separation boundary in **FIG. 9B** compared to **FIG. 9A**), there is an additional small irregular flow pattern just downstream of the turning lip at $\theta = 220^\circ$.

It is also notable that the angularity of the upper flow outside of the separated region somewhat weakens with the increase in $\dot{m}^*$, although its relaxation to axial inlet flow does not seem to differ much from the lowest flow rate case (i.e., the axial inlet flow becomes virtually uninterrupted by the crosswind within $330^\circ < \theta < 360^\circ$).

The flow topology becomes more complex once the flow rate increases to $\dot{m}^* = 0.94$ (**FIG. 9C**), primarily over the lower half of the visualized azimuthal domain. The trend of the upward azimuthal migration of the main separation segment continues in this realization as well, such that the upstream initial separation is centered at about $\theta = 240^\circ$; however, the azimuthal extent of this domain is diminished, while it still exhibits an upper circulating cell, which has a focus located at about $\theta = 275^\circ$. The overall separation extent upstream of the total pressure rakes is reduced to $250^\circ < \theta < 275^\circ$.

A major difference relative to lower flow rates is the appearance of multiple small circulating cells that develop on the lower surface, below the lower boundary of the main

separated region. The first cell is nested right next to the lower main boundary, at $\theta = 245^\circ$, midway between the inlet lip and the rake. Its circulating motion interacts with the smaller lip cell located just below $\theta = 240^\circ$, and their synchronous action drives the flow into the inlet between these two cells. The third cell, which is also located at the lip (at about $\theta = 215^\circ$),
 5 gives a rise to opposing flow angularity from below.

Hence, these two opposing flow angularities result in an apparent dividing streamline at about $\theta = 220^\circ$. In the remaining surface flow over the lower azimuthal section within $180^\circ < \theta < 210^\circ$, the outer flow is drawn axially into the inlet with almost no interference from the crosswind. Significant flow angularity is marked in the azimuthal segment
 10 immediately above the upper bound of the main separation region, and the higher angularity extends farther towards higher azimuthal angles and, as in all of the prior cases, the flow becomes axial close to the vertical plane ($\theta = 360^\circ$). Further evolution of the topology pattern is seen in the highest mass flow rate case (**FIG. 9D**). The main separation domain keeps shifting to the higher azimuthal angles, now centered at about $\theta = 270^\circ$, while the focal
 15 point of the upper-bound circulating cell is at about $\theta = 285^\circ$. The overall azimuthal extent of the main separated region is similar to the previous case but shifted upwards to the higher azimuthal angles. The two small circulation cells at the lip that are observed in **FIG. 9C** act in sync at the highest flow rate to form a small compact secondary separation region that mimics the main one. This secondary region is centered at just below $\theta = 240^\circ$, and it is
 20 bound by the circulating cell above and the extended separation cell along its lower boundary. Still, the axial extent of this secondary separated region is limited, and it does not extend to the streamwise positions of total pressure rakes.

Just as the secondary separation domain forms on the lower side of the main separation domain through the evolution of multiple small cells, a small initial cell appears to
 25 form at the inlet lip just below the secondary separated region. Further below, towards $\theta = 180^\circ$, the flow regains its nominal axial direction as is observed for all other presently considered flow configurations. Similarly, in spite of the additional upward azimuthal change in flow angularity outside of the main separation region, the flow becomes axial near $\theta = 360^\circ$.

30 As shown in **FIG. 10**, total pressure profiles for the same four inlet mass flow rates at a crosswind 35 knots are shown at each of the eight rakes. The upper row presents the rakes on the leeward side, which indicate almost no effect of the crosswind presence besides the gradual deepening of the total pressure loss close to the surface, just like for the increasing

inlet flow rate in the absence of the crosswind. Similar trend is seen at the bottom rake (180°), except that the loss becomes more pronounced.

The only three rakes that indicate notable changes with the crosswind presence are those oriented on the windward side, at 225°, 270°, and 315°. In accord with the oil views, the flow separation is strongest initially (lowest $\dot{m}^*$) at 225°, but opens up more, away from the surface, at 270° for $\dot{m}^* = 0.79$ (which obviously cannot be seen in the oil views). The azimuthal upward shift in the main separation domain at the two highest flow rates is reflected in the increasing total pressure deficit measured at 315°, while the deficits at 225° and 270° indicate higher outward extent of the deficit at 270°.

FIG. 10 includes the total pressure profiles corresponding to the oil images of **FIG. 9**. Radial distributions of the normalized total pressure $p^* = (p_o - p_a)/p_a$ that correspond to oil images in **FIG. 9** are shown in **FIG. 10**. **FIGS. 10A-10E** show that there is no real indication of total pressure losses on the leeward side (side away from the crosswind). This indicates that in most circumstances, control need only be applied on one side.

The effects of the separation are shown in **FIGS. 10F-10H**. The main losses are first measured at 225°, then with increased intake speed, the main loss spreads up to 270°, and finally for the two highest speeds, the losses even spread up to 315°. This indicates that the separation is able to spread significantly azimuthally and does not remain in one fixed spot as the intake speed is increased.

These data show that, despite the presence of the crosswind, the three azimuthal stations on the leeward side of the inlet (**FIGS. 10B-D**) exhibit a total pressure deficit near the surface that is related to the presence of the boundary layer. Interestingly, these distributions also show slightly reduced near-surface deficits when compared to similar profiles in the absence of the crossflow (**FIGS. 8B-D**). In accord with the surface oil flow images, both the top (**FIG. 10A**) and the bottom (**FIG. 10E**) total pressure distributions indicate that the flow about these locations is fairly insensitive to the presence of the crosswind and there is only a slight increase of the total pressure deficit compared to the flow in the absence of the crosswind.

As expected from the oil visualization images in **FIG. 9**, the main effects of the crosswind presence are on the windward side, i.e., at the rakes positioned at $\theta = 225^\circ$, 270° , and 315° (**FIGS. 10F-H**, respectively). The largest total pressure deficit with the fixed crosswind speed at the changing inlet mass flow rate occurs at $\theta = 225^\circ$ and 270° (**FIG. 10F**

and **FIG. 10G**, respectively). Both deficits exhibit the same outward radial extent away from the surface at the lowest inlet flow rate, having a more pronounced total pressure loss at $\theta = 225^\circ$, while there is an almost negligible increase in deficit at $\theta = 315^\circ$.

As the mass flow rate is increased to $\dot{m}^* = 0.79$ (**FIG. 10H**), the dominant radial p^* deficit is measured at $\theta = 270^\circ$, although it is similar to the distribution $\theta = 225^\circ$ and remains nearly unchanged at the upper section. It is interesting that the distributions of p^* deficit become very similar at $\theta = 225^\circ$ and 270° for the two highest inlet mass flow rates. In connection with the oil images in **FIG. 9**, an additional feature compared to the lower mass flow rates is the presence of p^* deficit at $\theta = 315^\circ$, as the main separation region shift towards higher azimuthal angles and flow angularity increases.

Similar to the already shown visualizations for the fixed crosswind, **FIG. 11** shows the three segmented oil-flow visualizations for the fixed inlet flow with the changing crosswind speed. It is interesting to note that the separation domain at 25 knots, although clearly defined, lacks the features of the bounding circulating cells, which are clearly present at the two higher crosswind speeds.

Aside from the same features already discussed with the previous visualization traces, it is interesting to note that the separation domain shifts azimuthally downward and widens in its extent when the crosswind speed is increased from 30 to 35 knots. As it was already shown that the trend is exactly the opposite with the increase in the inlet mass flow rate at the fixed crosswind, it is suggested that increasing the crosswind at the fixed flow rate is equivalent of reduction of the mass flow rate at the fixed crosswind.

In addition to the surface oil-flow visualization, the three windward total pressure profiles indicate the proportional increase in the deficit at 270° , similar, but much less pronounced effect at 225° , and essentially no difference at 315° .

Another aspect of the changing flow topology is evident when the crosswind speed is varied at a fixed mass flow rate through the inlet. Three such cases are considered in **FIG. 11**, where the oil flow images equivalent to **FIG. 9** are shown for $\dot{m}^* = 0.79$ at crosswind speeds of 25, 30, and 35 knots. **FIG. 11** explores what happens with increasing crosswind speed for a fixed intake speed. The effect is that the separation starts with just a velocity deficit at the wall, but is not strong enough to result in any reversed flow at 25 knots (**FIG. 11A**). At 30 knots (**FIG. 11B**) reversed flow appears, and the formation of circulation cells is seen. **FIG. 11C** represents 35 knots, and shows a greater spread in the separation as well as

the entire region moving downwards.

Even at the lowest crosswind speed (**FIG. 11A**), there is a clear boundary between the low-speed separated region and the outer flow. The separation horseshoe pattern is centered at $\theta = 245^\circ$ about the lip and exhibits streamwise broadening within $220^\circ < \theta < 270^\circ$.
5 Relatively mild angularity of the inlet flow is seen on either side of the separated region, which converges to the axial flow over extended azimuthal portions close to the inlet bottom surface, and even more so as the flow approaches the top surface (note that a large upper azimuthal segment starting at about $\theta = 300^\circ$ and extending up to 360° exhibits almost no interruptions of the nominally axial inlet flow).

10 As the crosswind speed is increased to 30 knots (**FIG. 11B**), the flow separation topology becomes accentuated and develops an azimuthal offset. The initial flow separation about the lip is centered about $\theta = 250^\circ$, and the two cell structures become clearly marked along the upper and lower boundaries of the separated domain. Aside from the azimuthal offset, the streamwise azimuthal spread is not significantly altered, but a larger extent of the
15 non-axial flow spreads in either direction compensating for the shift in the separation domain while compared to **FIG. 11A**.

The azimuthal extents of the axial flow over the lower and upper segments are about the same and somewhat reduced, respectively. The same separation topology further progresses when the crosswind speed is increased to 35 knots (**FIG. 11C**). However, this
20 time the azimuthal shift of the horseshoe pattern moves downward and is centered at the lip at about $\theta = 240^\circ$. Such an azimuthally downward displacement of the separation domain is expected as a result of the effective increase in the ratio between the crosswind speed and the inlet flow, as discussed in connection with the displacement of the separation pattern in **FIG. 9**. As a result of the increase in crosswind speed, the separation domain, the bounding
25 circulation cells, and the flow angularity outside of the separated domain all increase compared to 30 knots crosswind.

The relevant total pressure distributions on the windward side are shown in **FIGS. 11D-F**. As expected from the oil flow visualization for all three crosswind speeds, these data show that at $\theta \approx 315^\circ$ (**FIG. 11F**), there is no additional pressure deficit aside from what is
30 induced by the presence of the boundary-layer. The dominant total pressure deficit is measured at $\theta = 270^\circ$ (**FIG. 11E**), while there is a peak of a similar magnitude but lower radial extent at $\theta = 225^\circ$ (**FIG. 11D**). Furthermore, it is seen that the crosswind effect on the

total pressure deficit at $\theta = 225^\circ$ is consistent but weak, as discussed in connection with change in flow topology in that domain. The main changes in the total pressure deficit are observed at the horizontal plane on the windward side (**FIG. 11E**), where there is a progressive increase in both the deficit magnitude and its radial extent with crosswind speed.

5 The differences between the inlet flows in the absence and presence of lip flow separation due to the crosswind were further analyzed by comparing the characteristic wall static pressure distributions. Generally, the shape of examined profiles was indicative of the flow acceleration over the lip, past which the flow encounters an adverse pressure gradient.

10 It was also noted that, in the absence of a crosswind, the static pressure distributions at $\theta = 90^\circ$ and 270° are practically identical owing to the symmetry of the inlet about the vertical center plane. All the distributions except at $\theta = 180^\circ$ reach about the same pressure minimum $p^* = (p_o - p_a)/p_a \approx -0.55$, while at $\theta = 180^\circ$ there is a slightly higher pressure drop indicating a difference between the flow evolution at $\theta = 0^\circ$ and 180° . This difference results from the acceleration being somewhat higher over the bottom surface due to the
15 inclination of the inlet plane.

Static pressure distributions for in $\dot{m}^* = 0.74$ at crosswind speeds of 25, 30, and 35 knots are shown in **FIG. 12**, along with the corresponding distributions in the absence of crosswind (the static pressure distributions at $\theta = 0^\circ$ and 180° are omitted since there is virtually no difference between the presence and absence of crosswind, as indicated by the oil
20 trace images in **FIGS. 11A-C**). **FIG. 12** shows how the flow behaves for different crosswind speeds. See that the separation worsens at these speeds, and that the flow accelerates outside of the separated region.

The pressure levels become progressively elevated with increasing crosswind speed (**FIG. 12A**) indicating significant flow deceleration about the horizontal leeward lip.
25 Pressure distributions at $\theta = 210^\circ$ (**FIG. 12B**) indicate a smooth flow acceleration over the lip at the crosswind of 25 knots, but at 30 and 35 knots, there is a short streamwise leveling just inside the lip small local circulation cells that form in this region, as clearly captured in **FIG. 11B**.

The most dramatic crosswind effect is captured at $\theta = 240^\circ$ (**FIG. 12C**) which is
30 practically fully encompassed by the separated flow (cf. **FIGS. 11A-C**). Clear leveling of the pressure profiles past the turn around the lip indicates a rather abrupt separation regardless of the crosswind speed. In conjunction with the occurrence of separation just below $\theta = 270^\circ$,

the pressure distributions along the horizontal plane on the windward side (**FIG. 12D**) point to significant flow acceleration about the lip at this area, with a minimum that weakly decreases with the crosswind speed. A rather similar local flow acceleration about the lip is measured at the next azimuthal orientation $\theta = 300^\circ$ (**FIG. 12E**), but this acceleration almost
5 completely vanishes at $\theta = 330^\circ$ (**FIG. 12F**) indicating that the upper-most windward side flow is not altered in the presence of the crosswind even when the crosswind induces local separation elsewhere on the windward side of the inlet (as indicated by the oil visualization analysis of **FIG. 11**).

FIG. 13 shows how the mass flow rate decreases with crosswind speed as a result of
10 the ensuing separation. A global indication of the crosswind effect on the inlet flow is shown in terms of the variation of the inlet mass flow rate $\dot{m}^*$ with blower power in the absence and presence (25, 30, and 35 knots) of crosswind.

These data indicate similar trends in the drawn mass flow. First, there is a rather sharp increase at low blower power up to about $\dot{m}^* = 0.5$, followed by a gradual, smooth
15 diminution of its rate of increase and ultimately asymptotic approach to choking at high blower power where even small increases in mass flow rate require significantly higher power owing to increased losses associated with the appearance of shock waves. In spite of the similar mass flow variations, there is a clear difference between the mass flow rates in the presence and in the absence of crosswind. While in the absence of the crosswind, the flow
20 losses are mostly associated with the friction losses of stagnant flow being smoothly drawn into a high-speed duct, flow losses in the presence of crosswind stem from the turning of the crossflow into the inlet that are exacerbated by complex separation topology (cf., **FIGS. 9** and **11**).

In addition to characterization of the inlet flow in the presence of crosswind, the
25 present invention illustrates the utility of fluidic flow control based on distributed, passive aerodynamic flow of air between the outer and inner surfaces of the nacelle for mitigation of flow distortion and separation. This approach, which does not require a powered air source, builds on earlier research showing that the interaction between aerodynamic flow, that is adjusted by low-power, surface-integrated louver valves, and the crossflow can be tailored to
30 leverage the generation and regulation of vorticity concentrations on or near the surface to alter both attached and separated flows.

In the present invention, the aerodynamic flow is driven through the nacelle's shell by

the inherent pressure differences between the inner and outer windward surfaces and is only regulated by its interaction with the crossflow over the outer and inner shell surfaces. However, it is noted that regulated aerodynamic flow could enable time-dependent control of inlet flow separation and distortion in varying crosswind speed and direction and inlet mass flow rate during taxi, takeoff, and landing.

In an exemplary embodiment, flow ports having characteristic diameter $d = 0.009D$ are organized in axial arrays at equally spaced azimuthal angles. The centerline of the inlet of each flow path on the outer shell lies within the same azimuthal (r-x) plane through the nacelle's centerline as the outlet port on the surface of the inner shell. The choice of an array of flow ports is driven by the topology of the separation pattern in the base flow (in the absence of aerodynamic flow). The effects of aerodynamic flow control are first investigated using an azimuthal cluster of streamwise arrays that are centered about the azimuthal center of separation at 35 knots ($\theta = 240^\circ$, cf. **FIG. 11C**), such that the lengths of adjacent arrays taper off azimuthally in each direction. Perhaps the most pronounced effect of the aerodynamic flow actuation is the reduction in total pressure deficit at $\theta = 270^\circ$ even though the array of flow ports is centered about $\theta = 240^\circ$. Furthermore, an integral measure of the effect of flow control is provided by the change in the inlet mass flow rate (at a given operating point) relative to the uncontrollable flow. Direct measurements of the mass flow rate through the duct indicated that the tested aerodynamic flow control increased $\dot{m}^*$ by about 1.9% and 2.3% at 30 and 35 knots crosswind, respectively. This increase in $\dot{m}^*$ in the presence of aerodynamic flow results from reduction in flow losses in addition to the inherently added aerodynamic flow.

As noted earlier, the strongest total pressure deficit (and the total pressure distortion source) is centered at about $\theta = 270^\circ$ even though the oil visualization indicates that the inlet flow is not separated at this azimuthal angle. Rather, it is affected by the strong circulating cell that bounds the separated domain from above and appears to be nested just upstream of $\theta = 270^\circ$. This observation led to a second aerodynamic flow configuration having a similar azimuthal pattern but centered about $\theta = 270^\circ$. Again, the effect of the aerodynamic flow is mostly evidenced about $\theta = 270^\circ$. However, the increases in inlet mass flow rate are slightly higher: 2.6% and 2.4% for 30 and 35 knots crosswind, respectively.

A third aerodynamic flow control configuration was selected to be a double streamwise row of flow ports centered about $\theta = 270^\circ$. It is clear that this configuration induces different effects at crosswind speeds of 30 and 35 knots. While the pressure

recovery at 30 knots is comparable to the recovery of the first two aerodynamic flow configurations, the increase in mass flow rate is increased to 3.6% even though only 36% of the prior flow ports are used. This indicates that the effect of the actuation can be optimized by dynamically controlling the number and position of ports with changing flow conditions. This observation is underscored by the fact that when the crosswind speed is increased to 35 knots, the aerodynamic flow appears to impede the pressure recovery although there is still a slight increase of less than 1% in $\dot{m}^*$. Further investigations have shown that for a fixed power input, the mass flow rate through the inlet significantly decreases in the presence of crosswind (up to 50 knots). The effectiveness of passive autonomous aerodynamic flow configurations (i.e., without using control valves for regulation of the aerodynamic flow as shown in **FIG. 4**) was demonstrated in two operating modes.

First, it is shown that the blower power that is required to recover a desired mass flow rate at crosswind speed of 30 knots is reduced by about 10% by activating autonomous aerodynamic flow indicating a comparable power saving for full-scale engine operating under the same flow conditions.

Second, the benefits of the aerodynamic flow regulation are by measuring the aerodynamic flow-effected increment in inlet mass flow rate relative to the base flow for a fixed operating power. For example, at crosswind speeds of 30 and 35 knots, the respective increments in mass flow in the presence of aerodynamic flow relative to the conventional inlet were 7.3% and 6.7% again indicating comparable increments in full-scale engines.

FIG. 14 illustrates the effects of crosswind on the flow about an engine nacelle in ground operation, namely separation (**FIG. 14A**), internal separation in proximity to the nacelle inlet (**FIG. 14B**), and the formation of a ground vortex (**FIG. 14C**).

Initial tests for assessment of the aerodynamic flow regulation effectiveness were conducted at high crosswind speeds of 50 knots and the results are shown in **FIG. 15**. At this crosswind speed the flow on the inner surface of the windward nacelle section is separated (cf., **FIG. 14A**), and the aerodynamic flow is applied on this side (although it can also be used to effectively control the flow on the opposite surface). The aerodynamic flow was enabled through a cluster of ports **210** in three segments each comprising six azimuthal rows and six streamwise columns of flow ports that were tested by increasing the number of open rows, starting with the most upstream row. The port clusters were centered on three

azimuthal rays as shown in **FIG. 15** such that the radial centerline of the center segment (○) was aligned with the cross stream direction, and the centerlines of the two other segments (top (□), bottom (△)) were at 22° above and below the radial centerline of the center segment, respectively.

5 **FIG. 15** essentially shows how there is an effect of opening a larger or smaller area. This shows the effect of opening more rows of ports below center (△), above center (□), and centered on center (○). There is seen to be an optimal amount of rows before (at the peak) before the trend starts to decrease. This shows that there is a configuration of flow ports that produce a maximum benefit before diminishing. From data, this is shown to be a
10 configuration resembling the separation.

The measured mass flow rate for the center cluster exhibits an increase with the number of open aerodynamic flow rows up to a maximum of nearly 6% before encountering a decrease (○), while the nearly linear, lower (△) cluster exhibits a somewhat lower rate of increase, but monotonic with the number of adjacent rows of open flow ports.

15 It is noted that aerodynamic flow actuation on the upper cluster is not as effective because the internal separation is centered between the central and lower aerodynamic flow clusters (the baseline nacelle flow is not symmetric top and bottom). These data clearly indicate that in a practical implementation, the flow ports can be activated using internal valves, and therefore the aerodynamic flow configurations can be continuously altered based
20 on the actual operating conditions.

FIG. 16 notationally shows which flow ports are “activated” (i.e. opened) in the CAD. By simply opening these paths for the air to travel, there is a decrease in the overall total pressure losses as well as an increase in mass flow rate of ~2.1% for both 30 and 35 knots. If instead of having this aerodynamic flow configuration centered on the main
25 separation, it is moved upwards to also cover some of the flow angularity and circulation cells, **FIG. 17** shows a similar reduction in the total pressure losses as well as an increase in mass flow rate of ~2.5% for both 30 and 35 knots.

As shown in **FIG. 16**, the aerodynamic flow of air from the outer to the inner surface is first distributed over the main separation domain, as depicted in surface oil-flow
30 visualization at 35 knots. The aerodynamic flow was distributed in arrays of the flow channels in a triangular pattern. In spite of the pattern that was designed to follow the separation at 35 knots, application of the present aerodynamic flow resulted in an increase of

about 2% in the mass flow rate through the inlet at both 30 and 35 knots. The favorable aerodynamic flow effect is captured in the central horizontal plane (240°).

In a second exemplary configuration shown in **FIG. 17**, where the same aerodynamic flow pattern as **FIG. 16** is shifted azimuthally and centered at 270°, and the overall effect becomes slightly improved, yielding about a 2.5% increase in mass flow rate. Oil flow visualization for this aerodynamic flow pattern at 35 knots shows that, similar to the aerodynamic flow pattern centered at 240°, the flow control effect is captured in the total pressure profiles at 270°.

As shown in **FIGS. 18-19**, the flow ports are distributed as an array around the inlet, from the top at 306°, to the centerline at 270°, to the bottom at 230°. Rows of ports can be opened azimuthally around the inlet or opened along the streamwise direction going into the inlet. Data shows that, by opening up more streamwise rows, the “virtual surface” becomes thicker in the radial direction since one port will create flow at the wall, the next port will create flow over this flow, the next will create flow on top of that, etc.

Therefore, the thickness of the virtual surface can be altered by opening up more streamwise rows. In a similar fashion, the azimuthal extent of this separation can be changed by opening up more rows around the inlet.

Therefore, complex three-dimensional virtual surfaces can be created along the inner wall by carefully selecting which ports are open. For example, there is ability to control the radial extent, streamwise extent, and azimuthal extent of the new surface. A pattern such as the one shown below in **FIGS. 18-19** produces a surface with a triangular bump centered at 270° which is thicker at the center and tapers down as one moves azimuthally up/down, and also taper down as one moves in the streamwise direction into the inlet.

The same aerodynamic flow pattern is tested in the conditions that mimic an engine start in the pre-existing wind conditions. Therefore, the crosswind speed is preset to 35 knots, while the inlet mass flow rate is ramped up from zero to the maximum, and then ramped down back to zero.

In **FIG. 18**, time-resolved measurements at 1 Hz of the total pressure tubes at 270° are shown for the base and controllable flow such that their position y/R away from the surface designates the port position. Generally, the total pressure deficit increases with the mass flow rate, and also increases in the direction towards the surface. When comparing the

controllable with the base flow, it is seen that the controllable flow both suppresses the peak deficit closest to the surface and leads to the steeper recovery towards the bulk flow.

Airplanes are not run at a fixed speed, so it is important to observe the effect of the total pressure losses over time since the aerodynamic flow is dependent on the intake speed (more air will be drawn through the flow ports if the engine is sucking with higher power). For this reason, testing was done with steadily increasing the inlet mass flow rate over time, and then decreasing it back down. For the no aerodynamic flow case one can look at the total pressure losses of the 270° rake over time (where the largest loss was observed). The same was run for an aerodynamic flow configuration case.

Looking at a front view in **FIG. 19**, one can get a better idea of what the maximum total pressure loss looks like for this case. A significant reduction in the overall loss by 25% is seen for the aerodynamic flow case at maximum speeds. This indicates a smaller overall loss for the inlet after simply opening the flow ports allowing flow to move through them.

Instead of the full 3D representation of the transient effect, a somewhat simplified view is shown in **FIG. 19** as a normal projection, which emphasizes the most severe total pressure deficit that evolves at the total pressure probe closest to the surface. Here, it is seen that the base flow scaled deficit of about -0.35 plateaus at about -0.26 – a decrease of nearly 26%.

Because the previous configurations worked well for both 30 and 35 knots, a smaller aerodynamic flow configuration was considered for the 30-knot case since the separation was not as complex/radially extensive. In **FIG. 19**, it was instead chosen to simply aerodynamic flow air in the two highlighted rows. Doing so produced the plotted total pressure losses, which were significantly less for 30 knots. A similar effect for 35 knots was not seen, indicating that this aerodynamic flow configuration was not strong enough for this case. Nonetheless, a 3.6% increase in mass flow rate was realized for the 30-knot case.

To further test how the aerodynamic flow concentrated about the central horizontal plane (270°) affects the flow, only the two arrays of flow channels are kept open as shown schematically in **FIG. 20** and also seen in the oil-flow visualization at 30 knots crosswind. Although reducing the number of ports by 64%, this configuration results in the mass flow rate increase by about 3.5% for the crosswind speed of 30 knots. However, its effectiveness drops significantly at 35 knots, to only about 1% increase.

FIG. 21 is similar to **FIG. 19**, plotting the maximum total pressure loss over time (at 270°), where a reduction in maximum losses of 25% can be achieved by simply opening these port passages. Similar to the “engine start in crosswind” mimicking that was done for the best aerodynamic flow configuration at 35 knots, **FIG. 21** shows the results for the base and aerodynamic flow cases at 30 knots, in terms of the transient change of the most critical total pressure deficit at 270°, closest to the surface. Similar to the analysis at 35 knots, here the same trend of the deficit increase with the inlet mass flow rate, down to -0.32, while the controllable deficit plateaus at about -0.25 – a decrease of around 24%.

The innovative flow control methodology using distributed aerodynamic flow shows potential to pave the way for integrated control of nacelle inlet flow in propulsion systems. The aerodynamic flow actuation that is driven by the inherent pressure difference across the nacelle inlet surfaces can help mitigate unsteady inlet effects in propulsion systems both in takeoff and landing (e.g., separation bubble, unsteady cross-wind, ground effects) and during flight (rapid climb or descent). In addition to regulation of mass flow rate (and therefore thrust) for a given engine pressure ratio (EPR), aerodynamic flow control can also mitigate inlet distortion and interactions with the compressor blades which can cause blade damage and compressor stall.

The present invention explores the topology of the three-dimensional flow and the evolution of complex separation cells over the windward inlet lip of a nacelle in the presence of crosswind. The flow topology is investigated to assist in inlet flow control selection to mitigate adverse effects of separation and distortion. The end objective is to enable integrated nacelle designs that can be dynamically optimized for varying flow conditions during taxi and takeoff/landing without compromising performance in cruise conditions.

The inlet flow in a nacelle model powered by a controllable blower and operating in suction was investigated in a cross-flow wind tunnel. In the absence of crosswind, the outer flow is drawn smoothly into the inlet, and the only deficit in the flow’s total pressure is associated with the inlet surface boundary layers. However, the presence of crosswind induces gradual thickening of the deficit region on the windward side of the internal surface of the inlet even prior to the appearance of local separation (at crosswind speed of about 25 knots).

The separation domain has a characteristic horseshoe-like streamwise boundary and is azimuthally tilted owing to the inclination of the nacelle’s inlet plane, and the degree and

direction of the tilt varies with the magnitude of the crosswind. The losses associated with the appearance of flow separation in the presence of crosswind lead to a reduction in the nacelle's mass flow rate compared to the nacelle's flow rate at the same blower power in the absence of crosswind. As the flow separation occurs at high crosswind speeds, the leading
5 edge of the horseshoe separation domain starts just downstream from the apex lip below the central horizontal plane. At lower crosswind speeds, the separation domain begins to shift azimuthally upward but becomes bounded by two additional separation cells at each azimuthal end. Further diminution of the crosswind speed displaces the main separation domain further azimuthally upward and additional secondary separation cells develop and
10 begin to merge and form additional horseshoe separation domains that closely resemble the main domain.

In the present investigation, a novel flow control approach based on scalable, distributed passive air aerodynamic flow through the nacelle's shell is explored for mitigation of flow separation and distortion. The aerodynamic flow is driven through configurable ports
15 in the shell by the inherent pressure differences between the inner and outer surfaces and does not require a powered air source. The aerodynamic flow is applied through streamwise rows of ports that are equally-spaced azimuthally with the objective of modifying the flow azimuthal asymmetry in the presence of crosswind. The effectiveness of aerodynamic flow actuation is demonstrated in three aerodynamic flow configurations that were based on the
20 topology of the separated base flow at a given inlet mass flow rate and the two crosswind speeds of 30 and 35 knots.

Aerodynamic flow configurations that encompass the primary separation domain can lead to diminution of the flow distortion (as measured by radial distributions of the total pressure) and increase the inlet mass flow rate by about 3%. It is also shown that only two
25 streamwise aerodynamic flow rows (36% of the initial ports) centered at the same azimuthal position as the larger array lead to a similar reduction in distortion and a larger intake mass flow rate. This finding indicates that fewer streamwise dynamically configured flow ports using integrated surface valves can be tailored to optimally control time-dependent separation and flow distortion at varying crosswind speed and engine power during taxi, takeoff, and
30 landing.

Numerous characteristics and advantages have been set forth in the foregoing description, together with details of structure and function. While the invention has been disclosed in several forms, it will be apparent to those skilled in the art that many

modifications, additions, and deletions, especially in matters of shape, size, and arrangement of parts, can be made therein without departing from the spirit and scope of the invention and its equivalents as set forth in the following claims. Therefore, other modifications or embodiments as may be suggested by the teachings herein are particularly reserved as they

5 fall within the breadth and scope of the claims here appended.

CLAIMS

What is claimed is:

1. An airflow control system comprising:

an aircraft engine;

5 a nacelle for the aircraft engine, the nacelle open at an inlet lip and extending rearward from the lip with a windward outer surface and an inner surface; and

an inlet flow separation abatement arrangement having an operational condition providing inlet flow separation abatement;

wherein the nacelle inlet lip is configured to experience an inlet flow therethrough;

10 wherein the physical geometries of the nacelle inlet lip leads to a range of uncontrollable inlet flow separation in proximity to the inlet lip during aircraft engine operation when the inlet flow separation abatement arrangement is not in the operational condition;

15 wherein the inlet flow separation abatement arrangement, when in the operational condition, leads to a range of controllable inlet flow separation in proximity to the inlet lip during aircraft engine operation; and

wherein the amount of uncontrollable inlet flow separation is greater than the amount of controllable inlet flow separation.

2. The airflow control system of Claim 1, wherein the inlet flow separation abatement arrangement comprises an aerodynamic flow arrangement of ports in the windward outer and inner surfaces of the nacelle in proximity to the inlet lip, the aerodynamic flow arrangement configured to allow passive aerodynamic flow through the ports from a high pressure to a lower pressure.

25 3. The airflow control system of Claim 1, wherein the inlet flow separation abatement arrangement comprises an aerodynamic flow arrangement of ports in the windward outer and inner surfaces of the nacelle in proximity to the inlet lip, the aerodynamic flow arrangement configured to allow passive aerodynamic flow through the ports from the windward outer surface to the inner surface.

4. The airflow control system of Claim 1, wherein when the inlet flow separation abatement arrangement is not in the operational condition, a virtual geometry of the nacelle inlet lip comprises only the physical geometries of the nacelle inlet lip, leading to the uncontrollable inlet flow separation in proximity to the inlet lip during aircraft engine
5 operation; and

wherein when the inlet flow separation abatement arrangement is in the operational condition, the virtual geometry of the nacelle inlet lip comprises an alteration of the physical geometries of the nacelle inlet lip, leading to the controllable inlet flow separation in proximity to the inlet lip during aircraft engine operation.

10 5. The airflow control system of Claim 1, wherein power to the aircraft engine during uncontrollable inlet flow separation presents a range of uncontrollable mass flow rates in proximity to the nacelle inlet lip;

wherein the same power to the aircraft engine during controllable inlet flow separation presents a range of controllable mass flow rates in proximity to the nacelle inlet
15 lip; and

wherein the controllable mass flow rates are at least 103% of the uncontrollable mass flow rates.

6. A nacelle for a gas turbine engine system comprising:

a housing having an inlet and an exhaust, and a pressure windward outer surface and a
20 suction inner surface; and

an aerodynamic flow arrangement of ports in the pressure windward outer and suction inner surfaces of the housing in proximity to the inlet, the aerodynamic flow arrangement configured to allow passive aerodynamic flow through the ports from the pressure windward outer surface to the suction inner surface.

25

7. A gas turbine engine comprising:

a nacelle defining an interior space;

a fan section, a compressor section and a turbine section positioned within the nacelle,
an inner cowl surrounding the compressor section and the turbine section, and the fan section
5 delivering air to the compressor section; and

flow control for selectively controlling the range of the flow of air through an
aerodynamic flow arrangement of ports in the nacelle and upstream the fan section, the ports
extending from outside the nacelle into the interior space of the nacelle.

8. In a method of aerodynamic control through media including:

10 operating an engine at power levels through a range of operating stages, wherein the
engine is within a nacelle having an inlet, and wherein mass flow rates of media in proximity
to the nacelle inlet correlate with the power levels; and

measuring the efficiency of engine operation;

15 in order to aerodynamically control the operation of the engine through the range of
operating stages;

the improvement comprising the step of adjusting nacelle inlet media flow separation
with passive aerodynamic flow control, including flow ports in proximity to the nacelle inlet;

20 which step of adjusting nacelle inlet media flow separation with passive aerodynamic
flow control provides higher efficiency of engine operation than the efficiency of engine
operation with a nacelle inlet without passive aerodynamic flow control as determined by
power level.

9. The method of Claim 8, wherein the operating stages are selected from the group
consisting of taxi, takeoff, climb, cruise, descent and landing.

25 10. The method of Claim 8, wherein adjusting nacelle inlet media flow separation with
passive aerodynamic flow control provides at least 3% higher efficiency of engine operation
than the efficiency of engine operation with a nacelle inlet without passive aerodynamic flow
control.

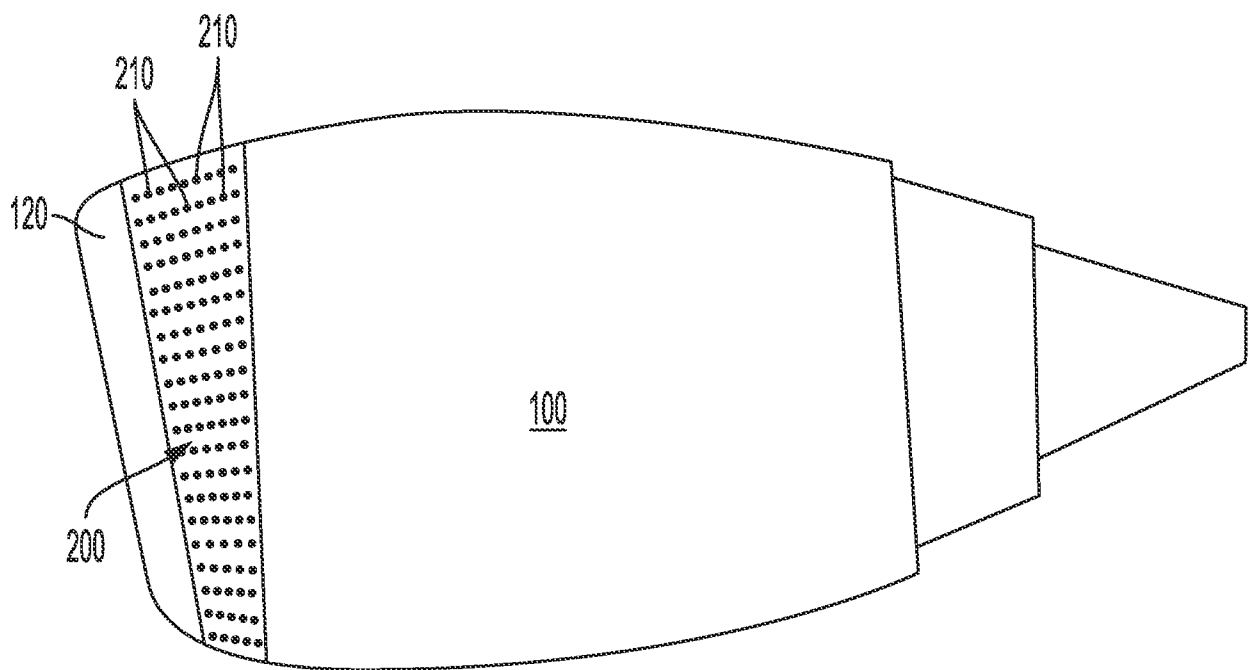
30 11. The method of Claim 8, wherein adjusting nacelle inlet media flow separation with
passive aerodynamic flow control provides at least 6% higher efficiency of engine operation
than the efficiency of engine operation with a nacelle inlet without passive aerodynamic flow

control.

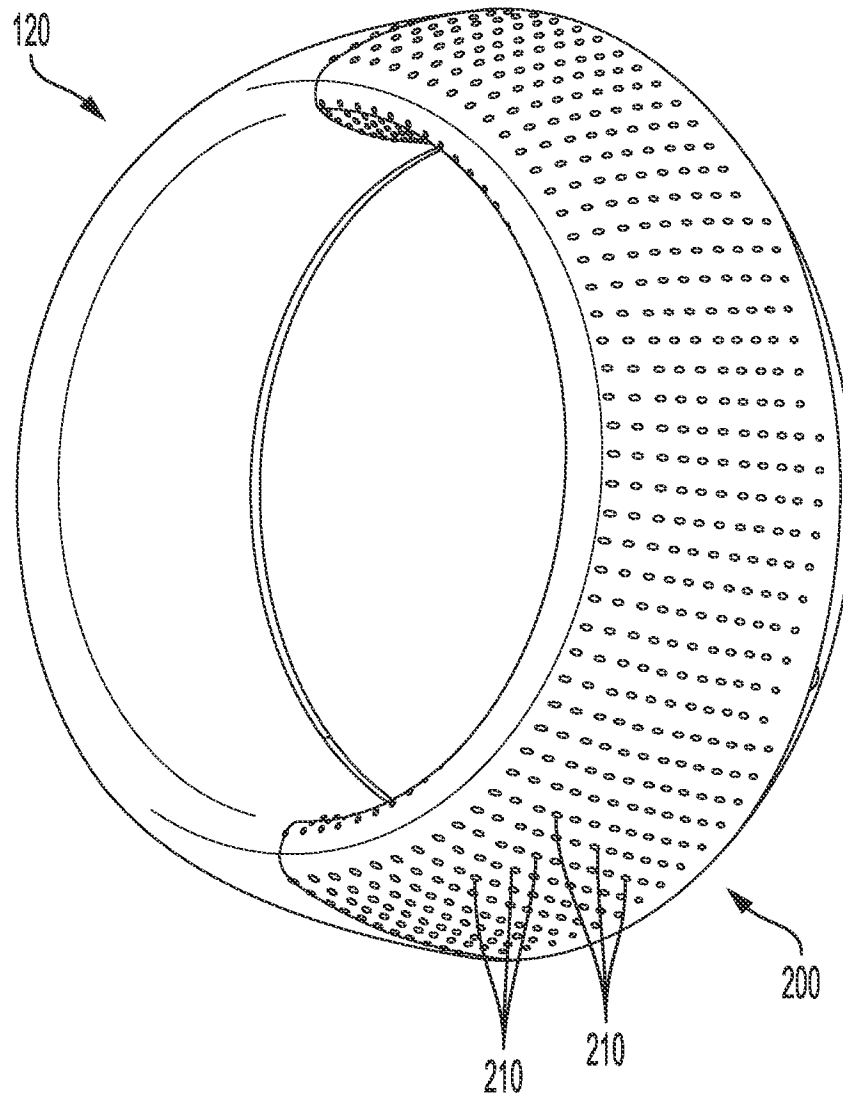
12. The method of Claim 8, wherein adjusting nacelle inlet media flow separation with passive aerodynamic flow control provides at least 10% higher efficiency of engine operation than the efficiency of engine operation with a nacelle inlet without passive aerodynamic flow

5 control.

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**FIG. 1**

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**FIG. 2**

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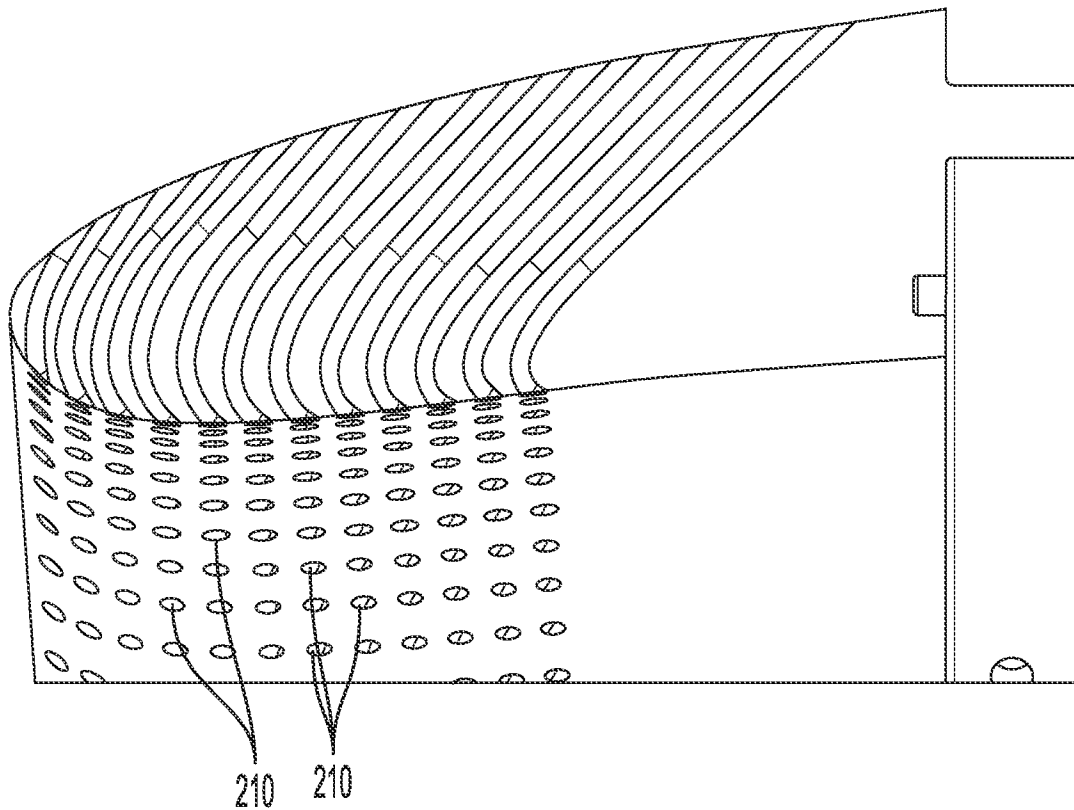


FIG. 3

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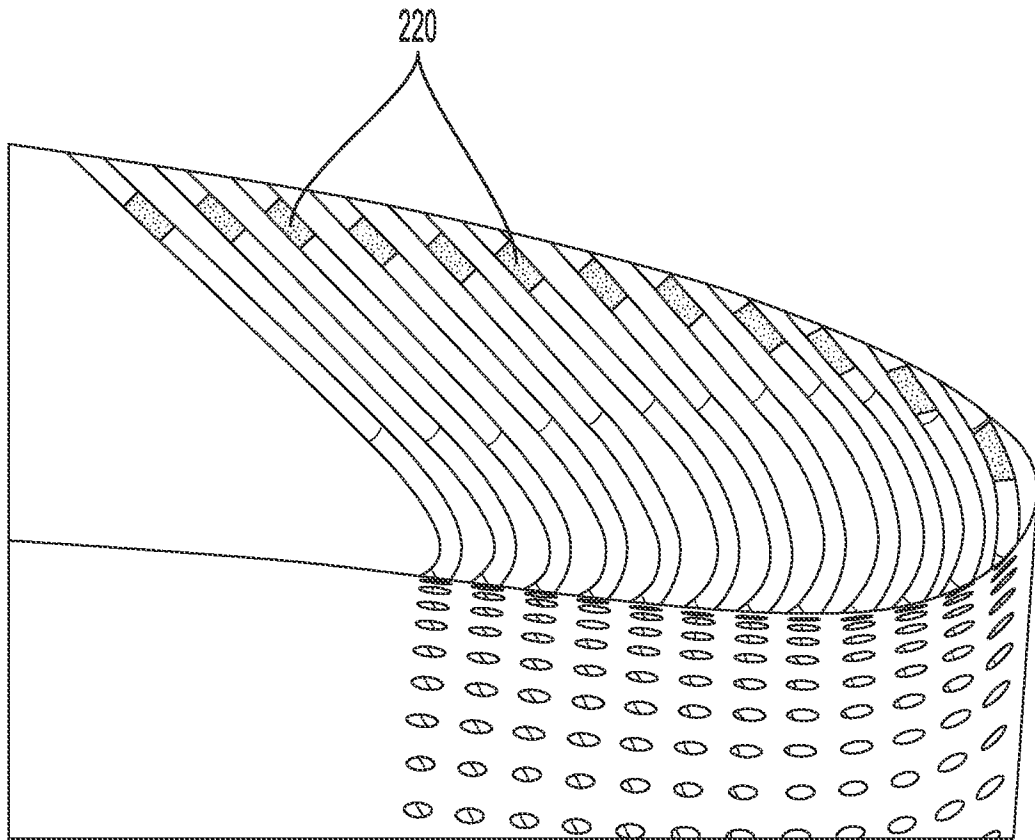


FIG. 4

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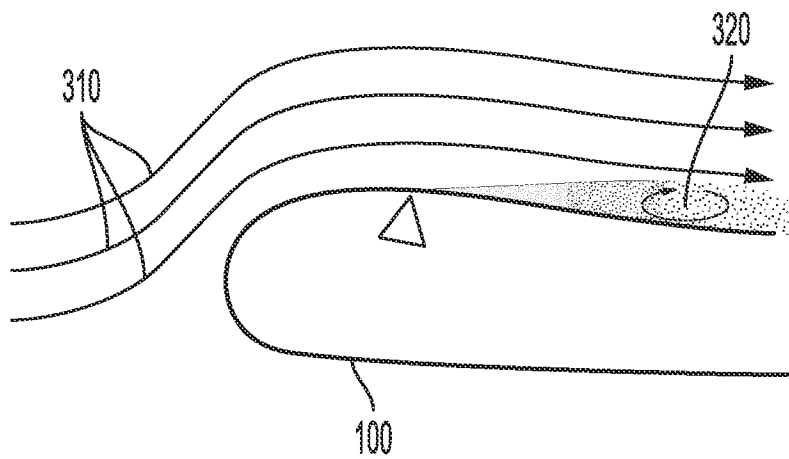


FIG. 5A

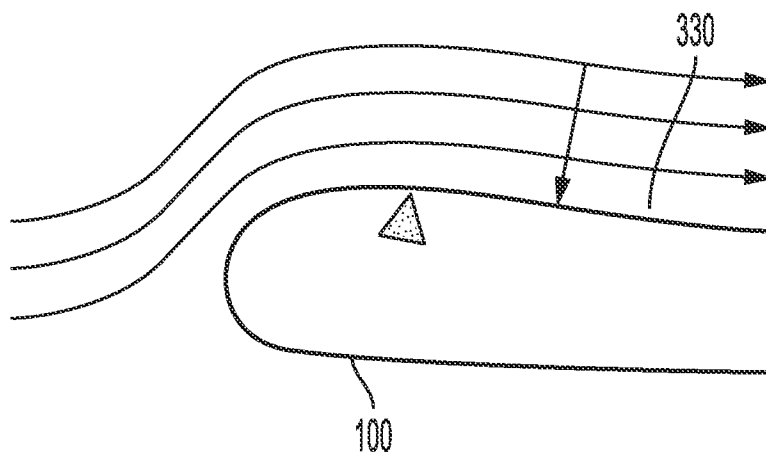


FIG. 5B

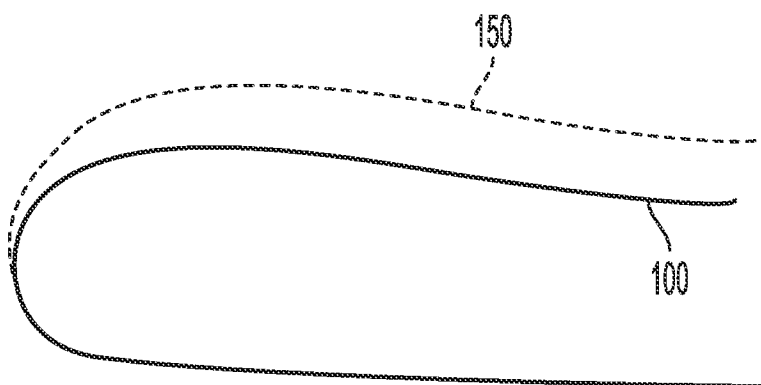


FIG. 5C

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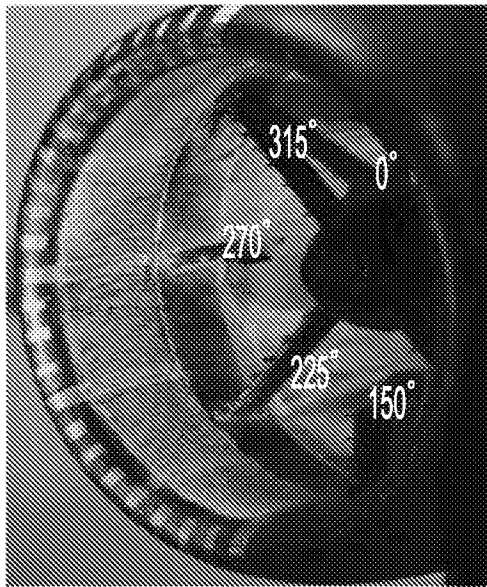


FIG. 6A

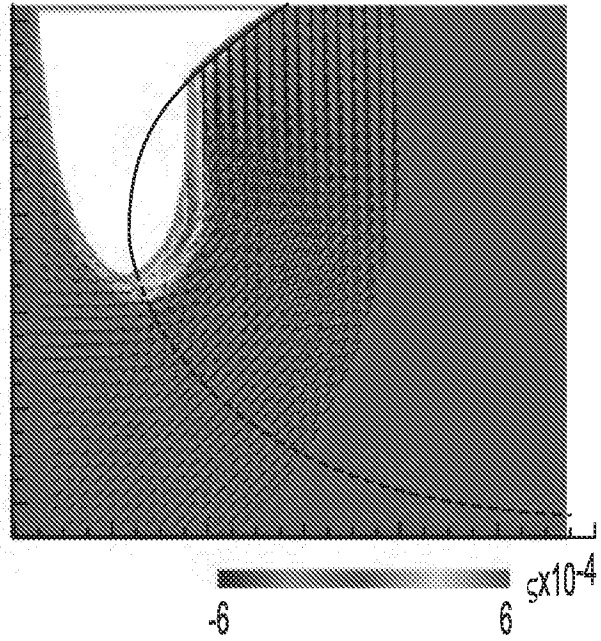


FIG. 6B

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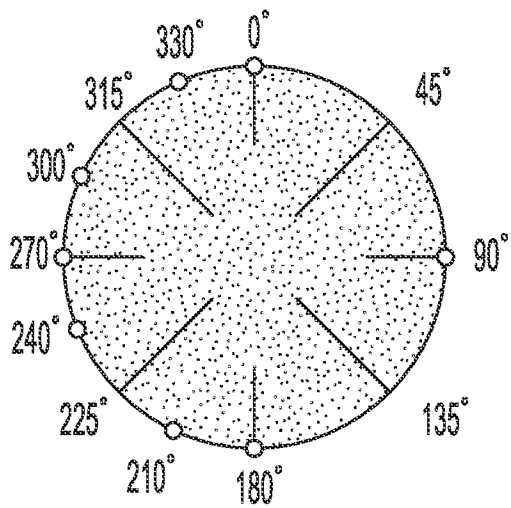


FIG. 7A

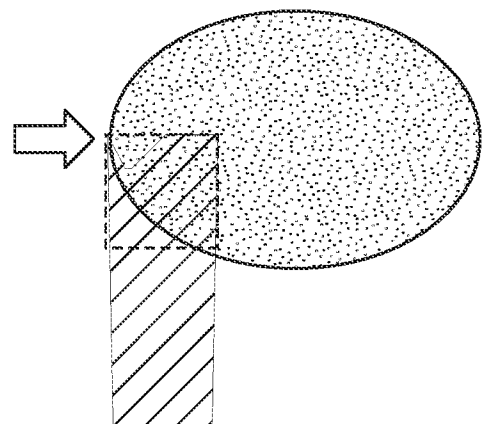


FIG. 7B

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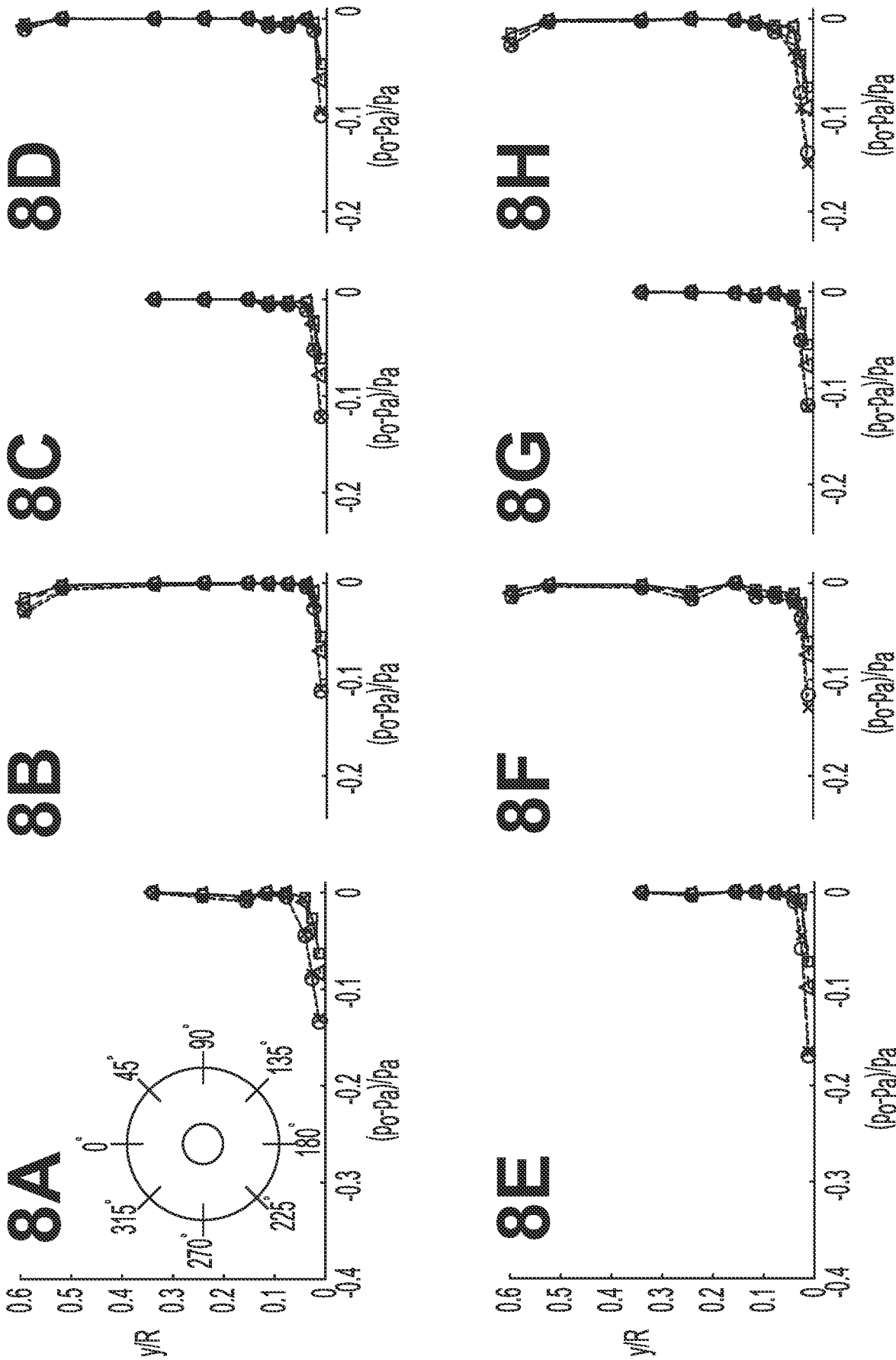


FIG. 8

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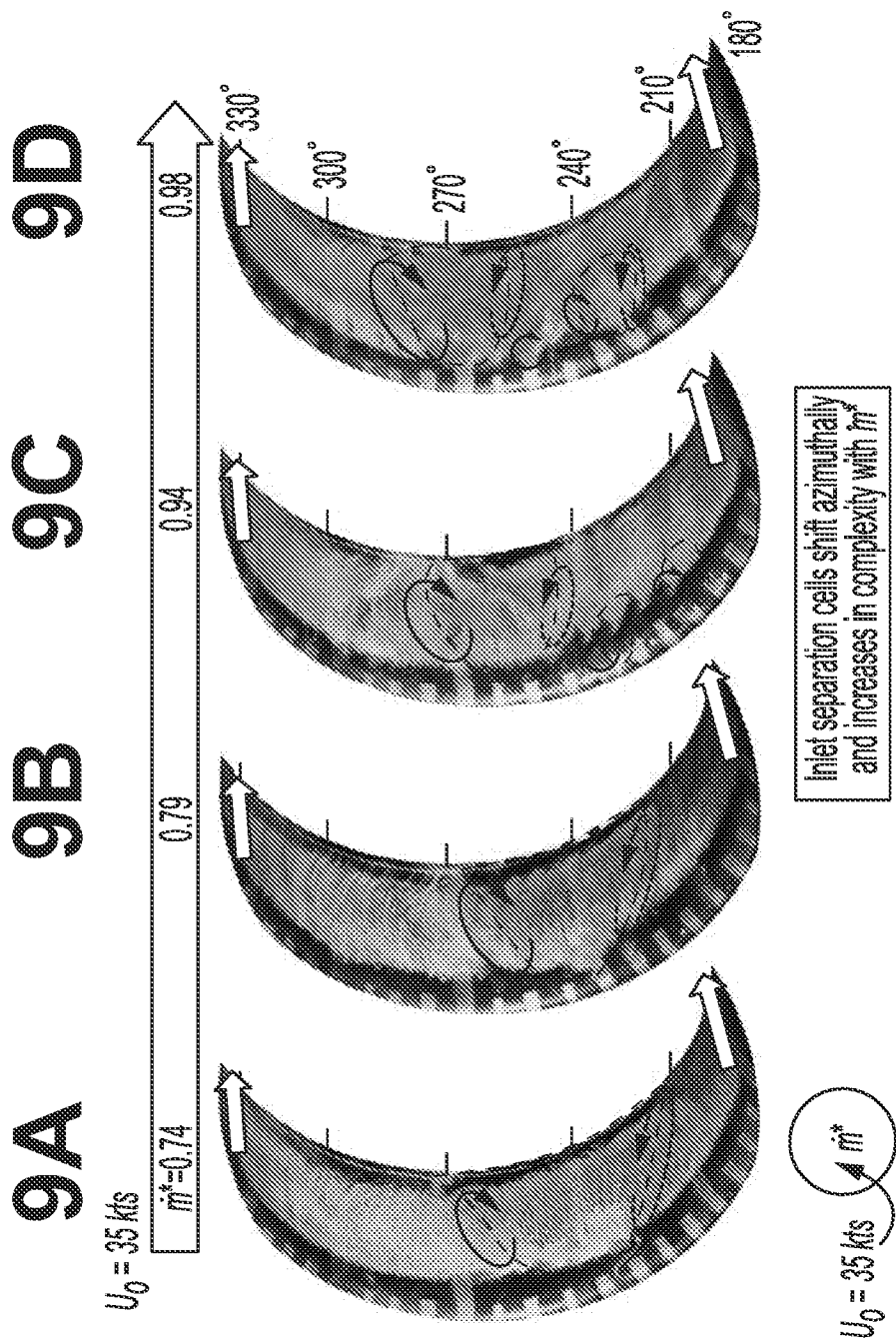


FIG. 9

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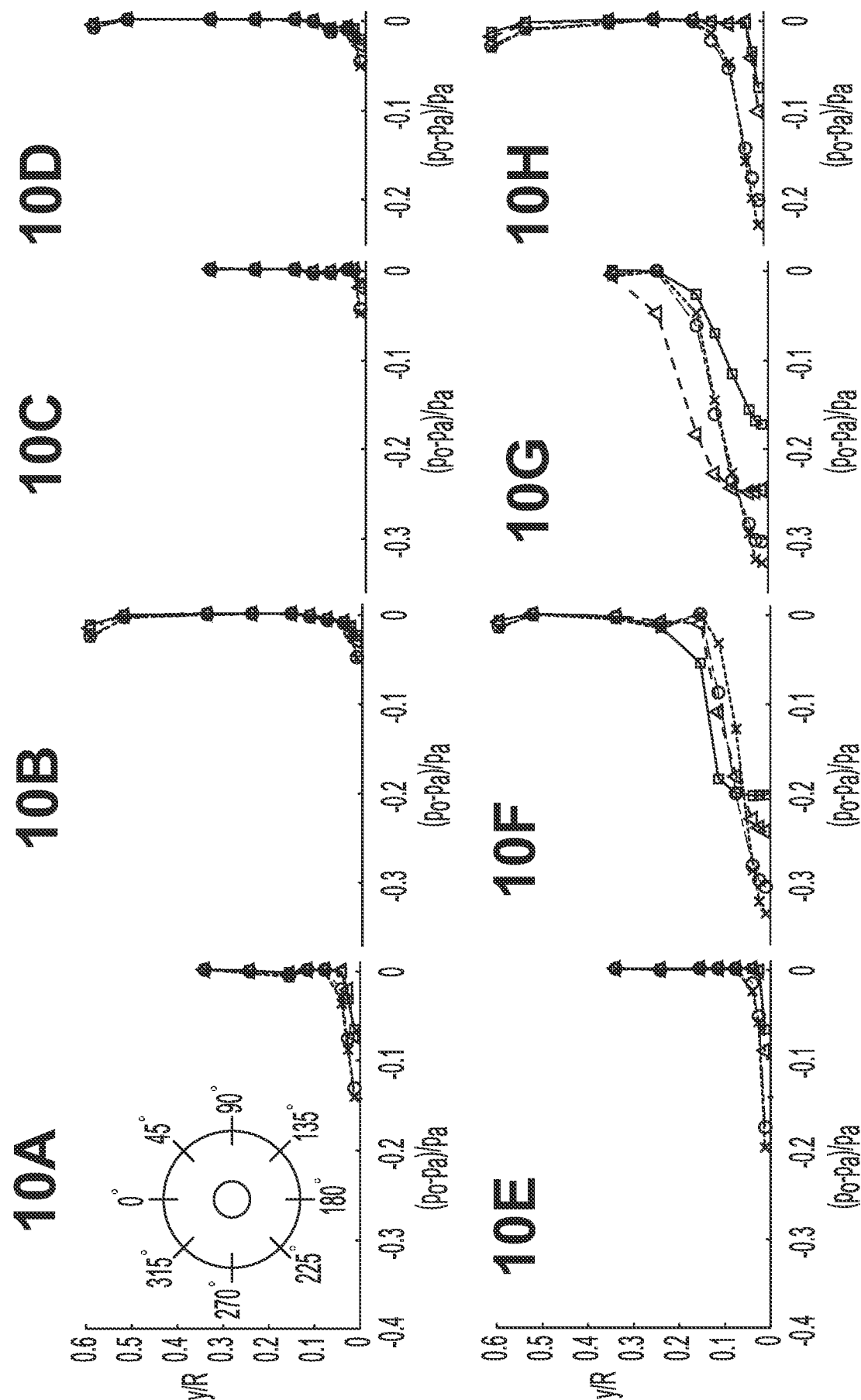


FIG. 10

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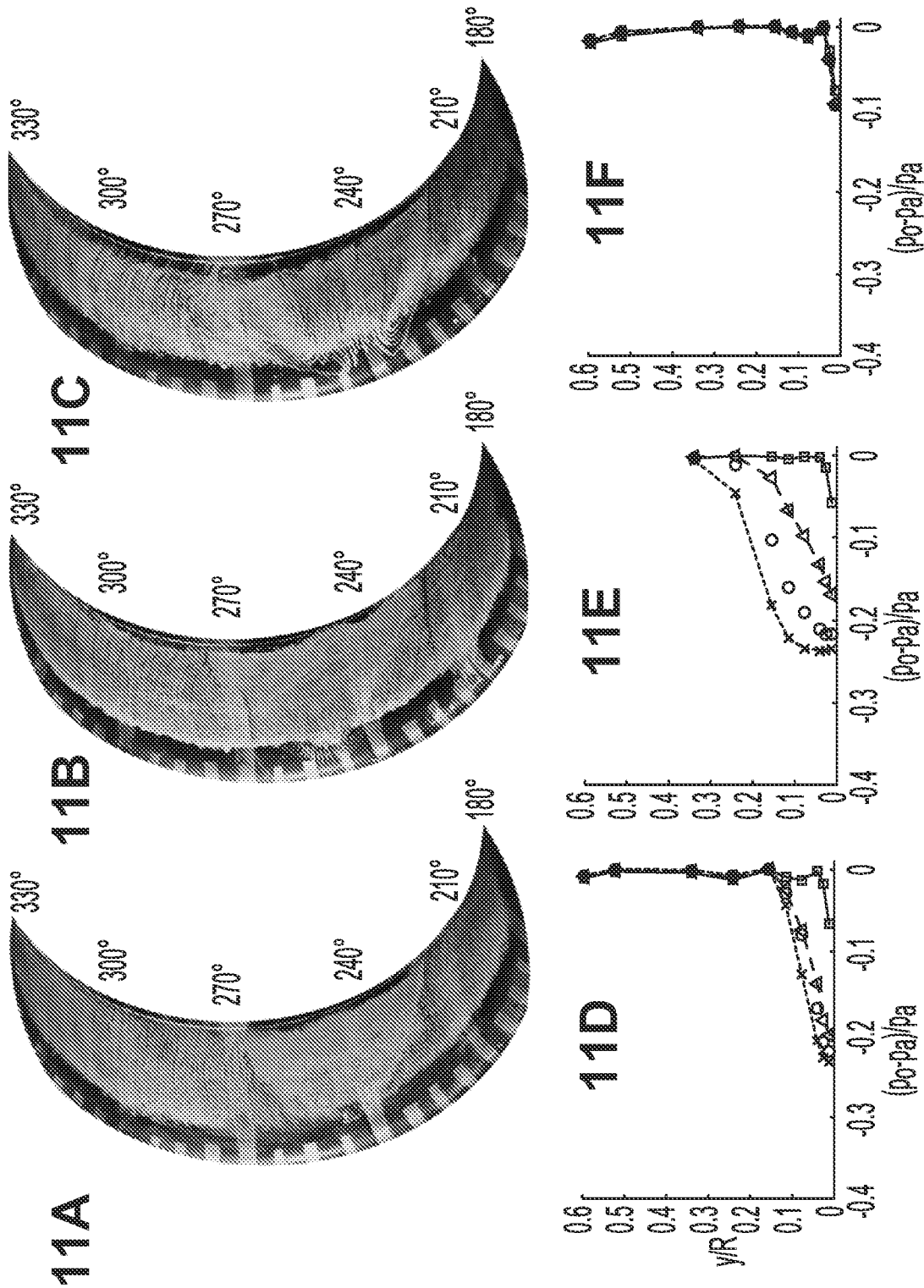


FIG. 11

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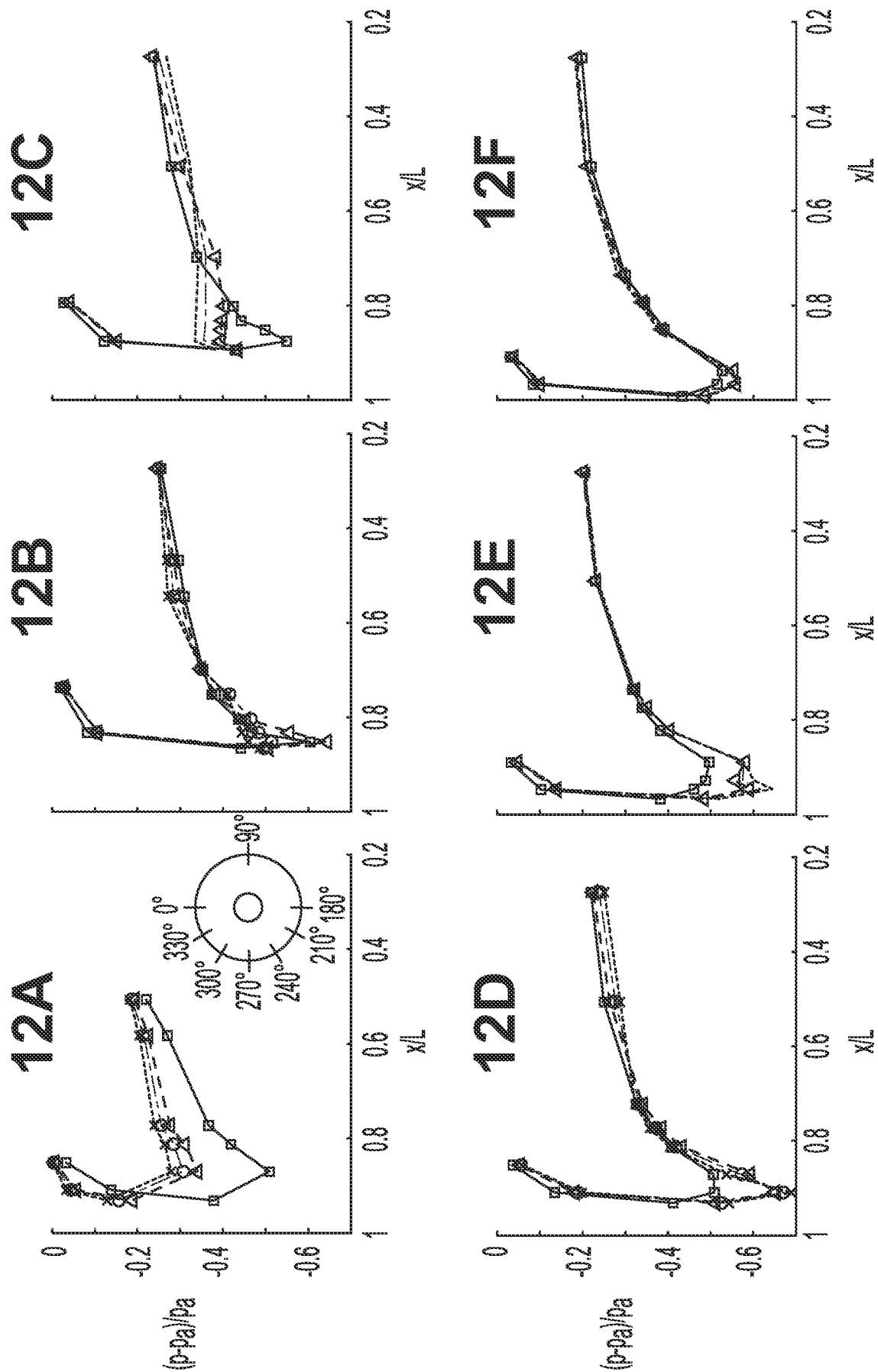


FIG. 12

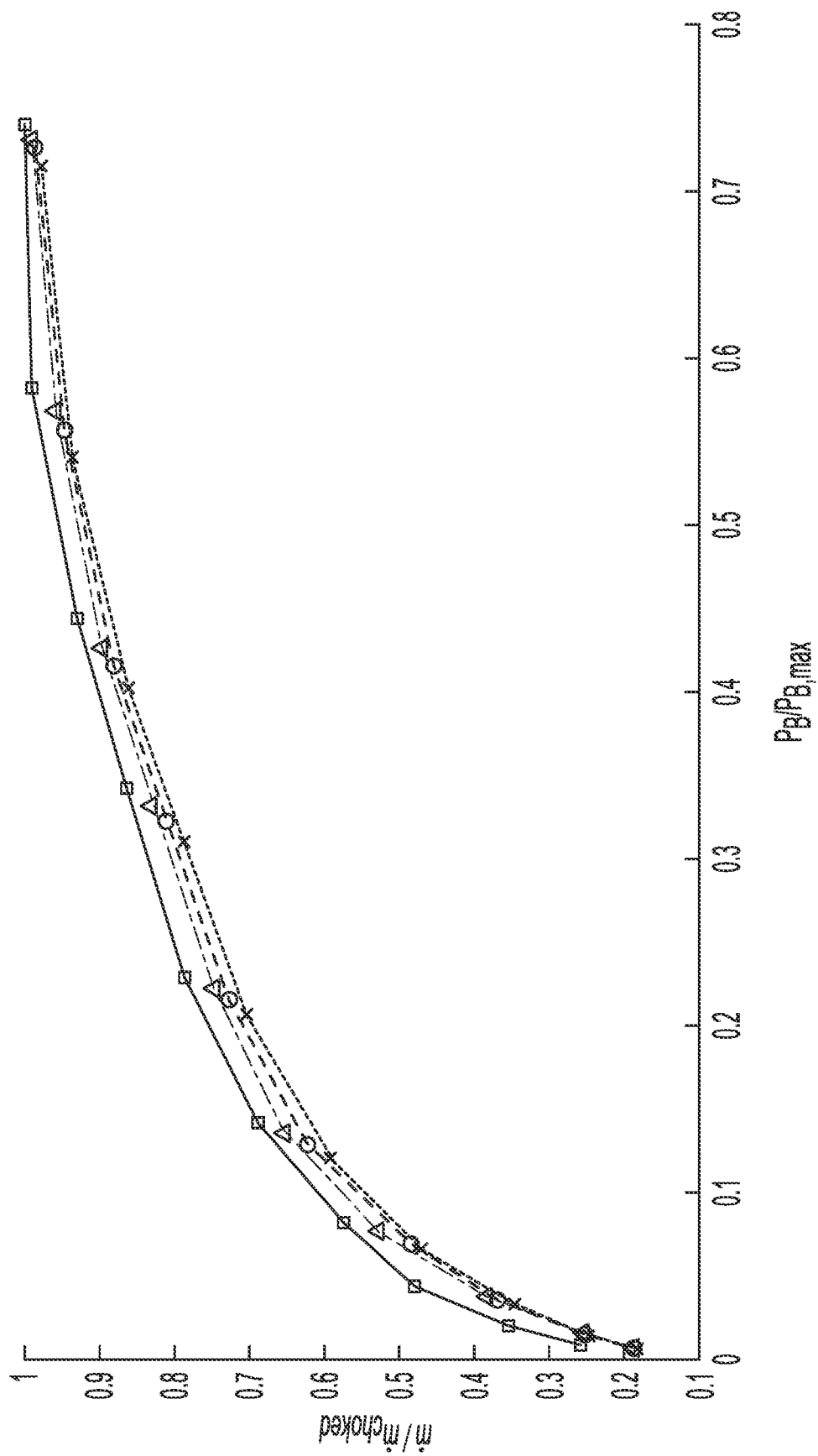


FIG. 13

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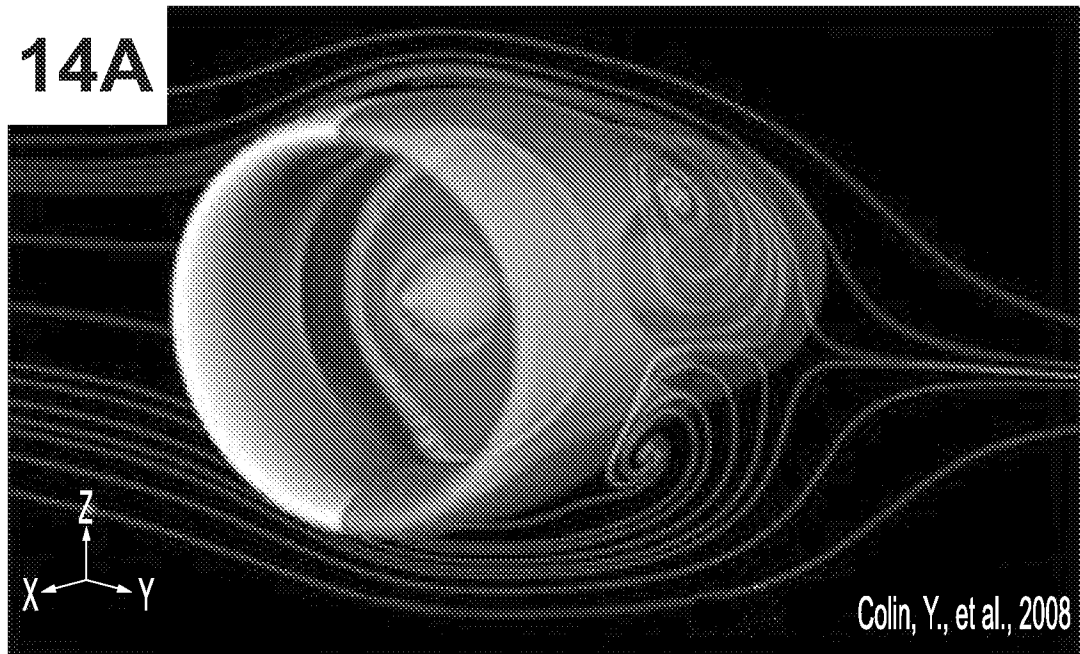


FIG. 14A

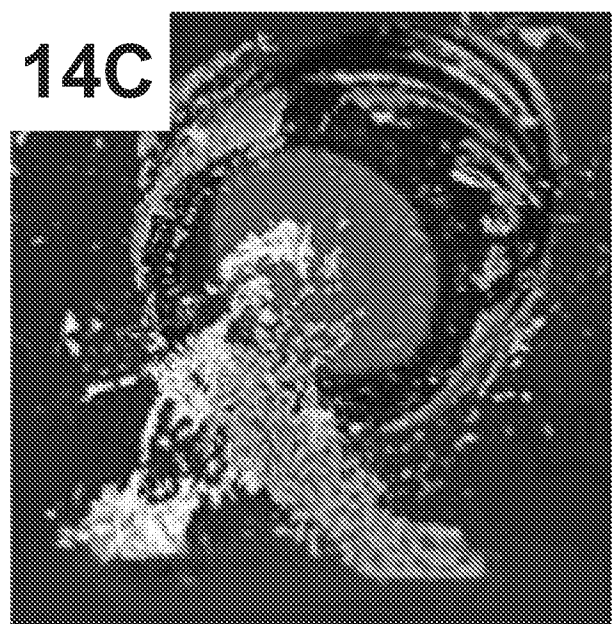
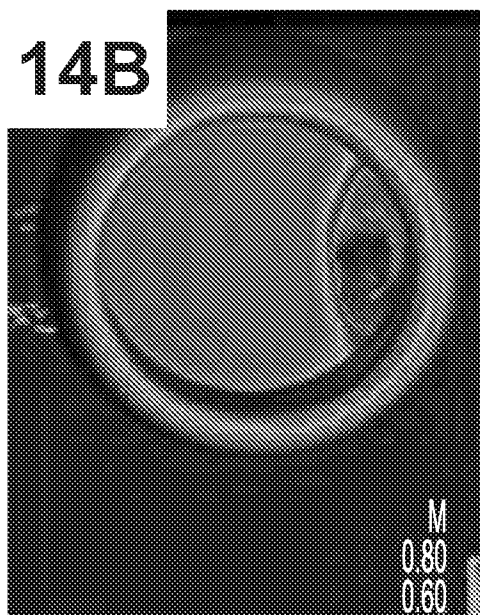


FIG. 14

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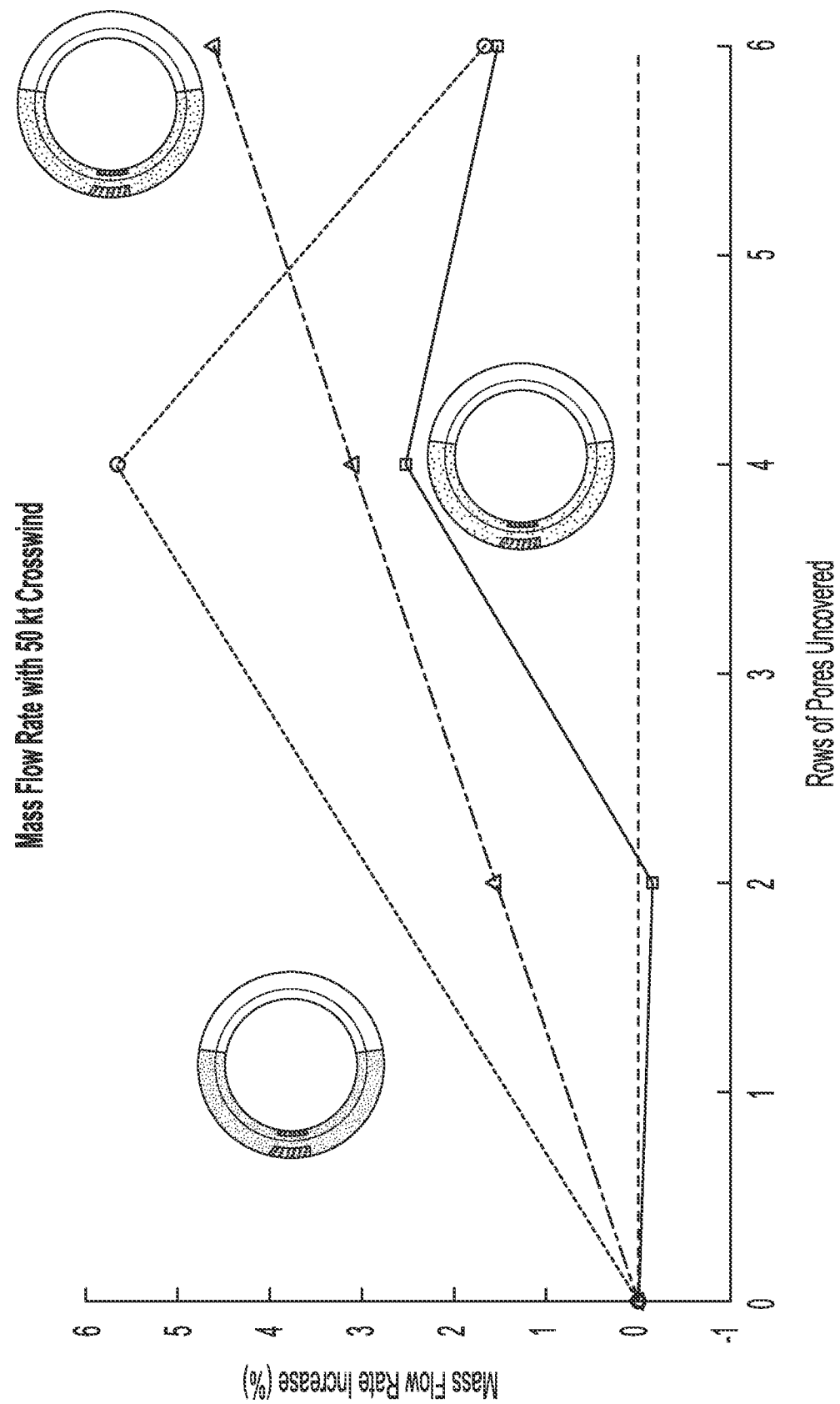


FIG. 15

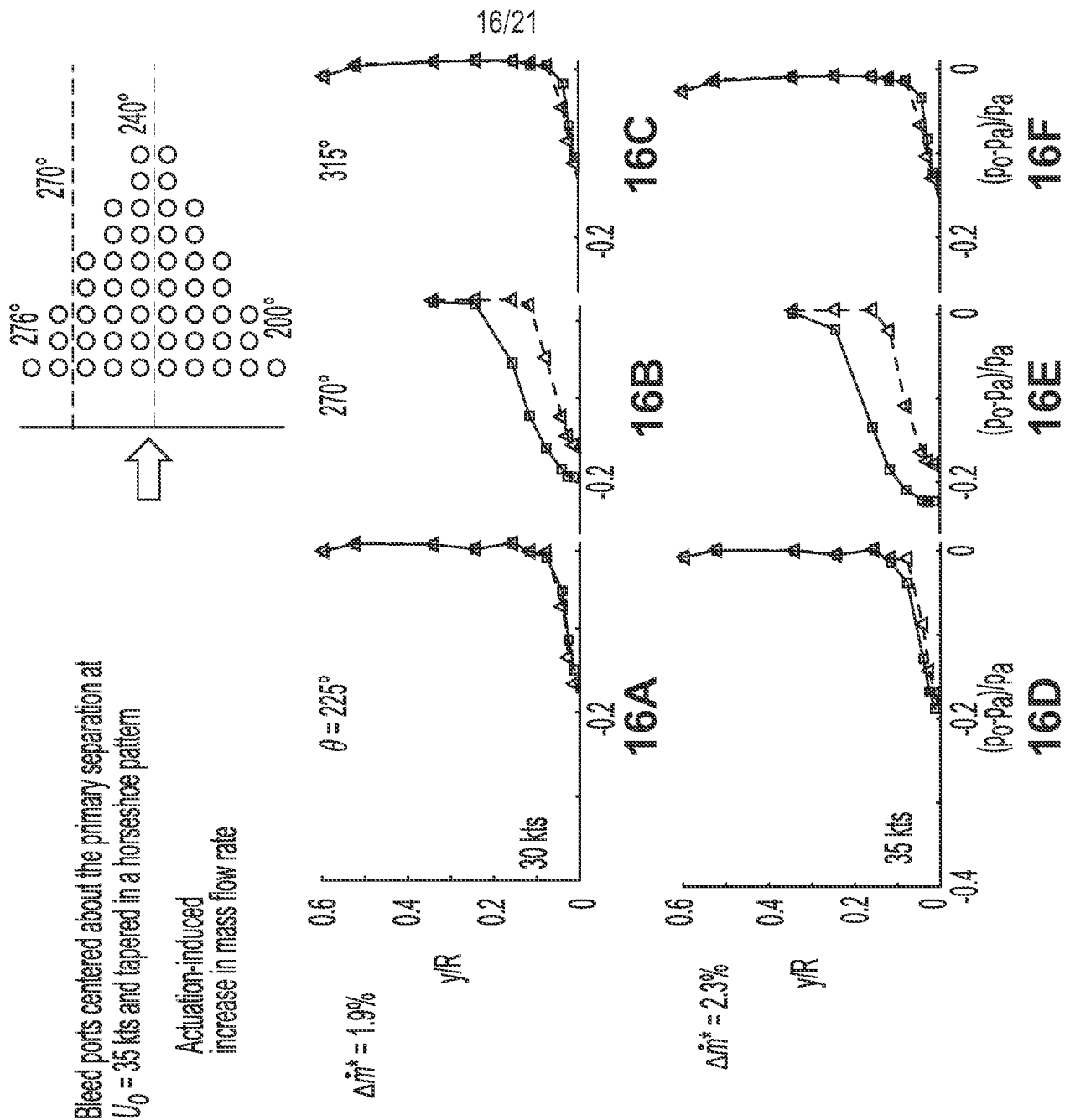


FIG. 16

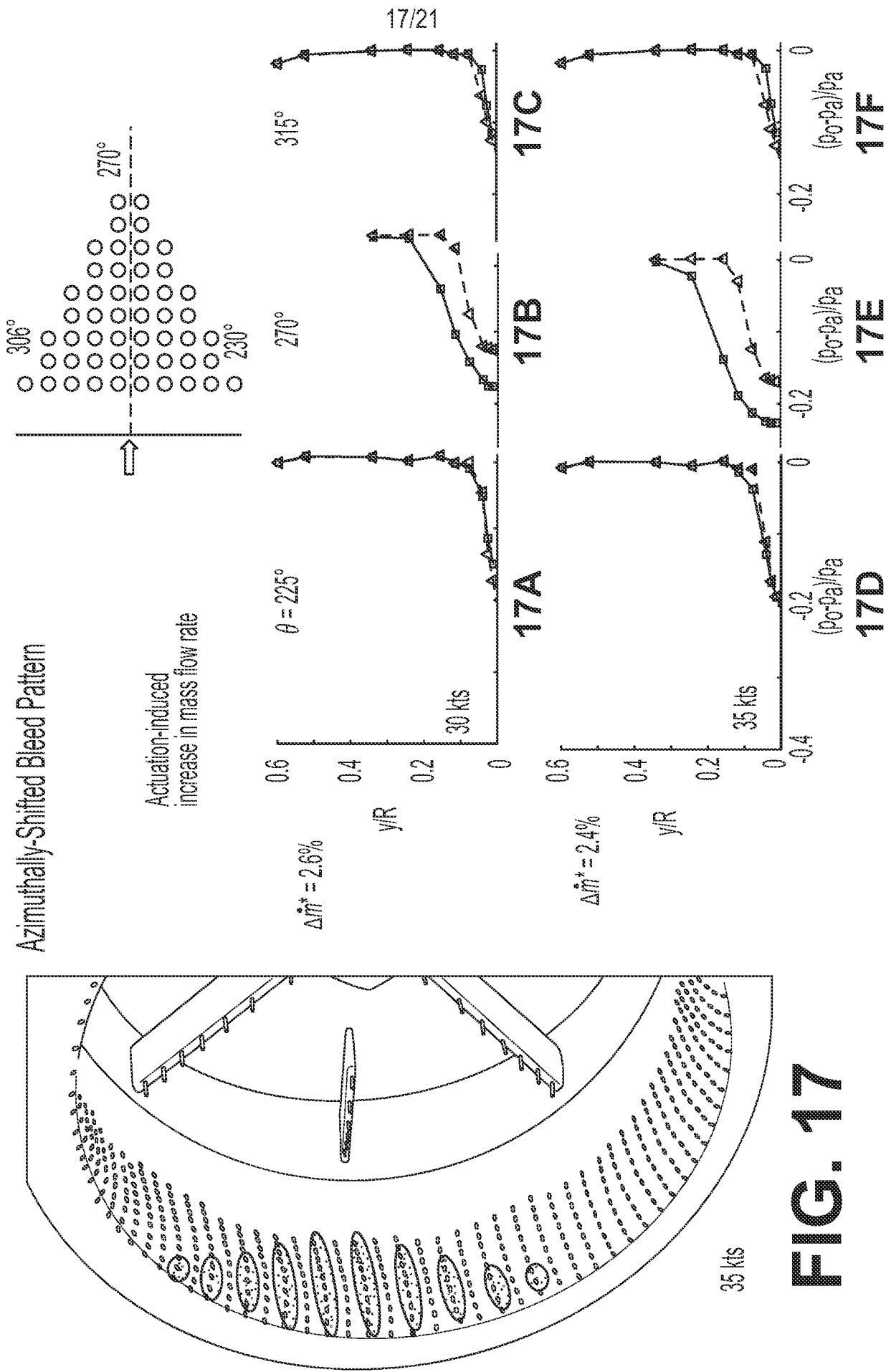


FIG. 17

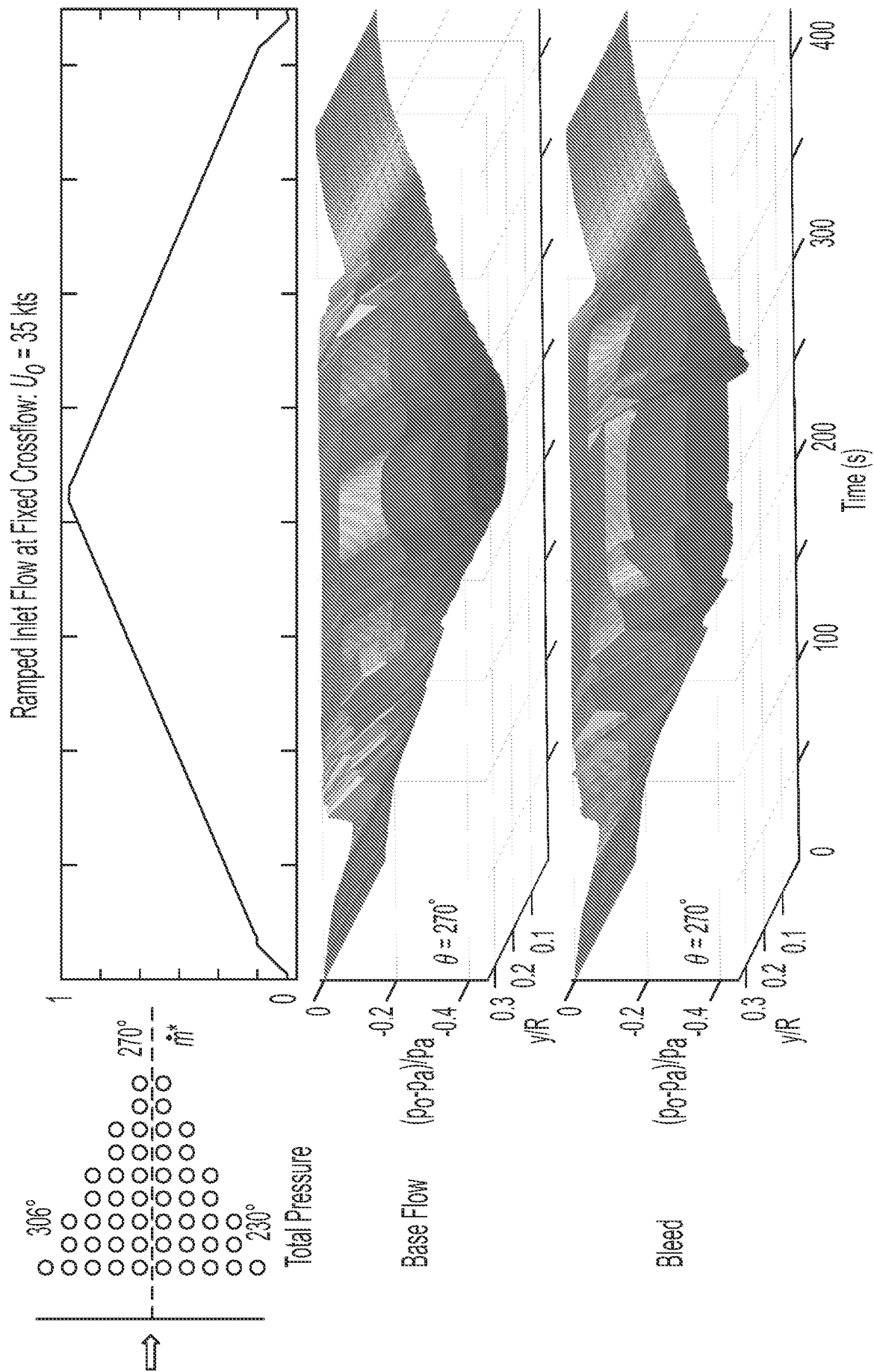


FIG. 18

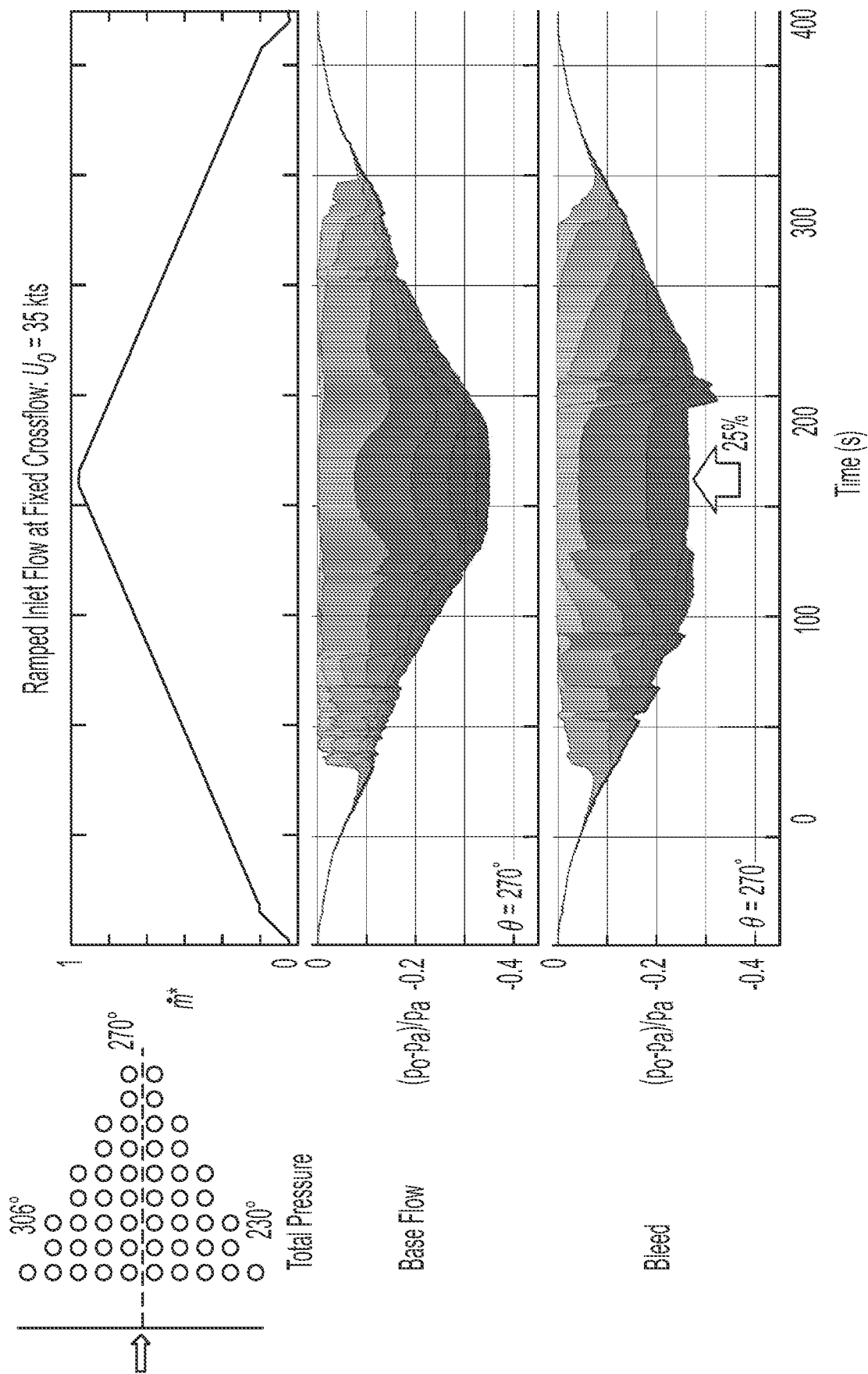


FIG. 19

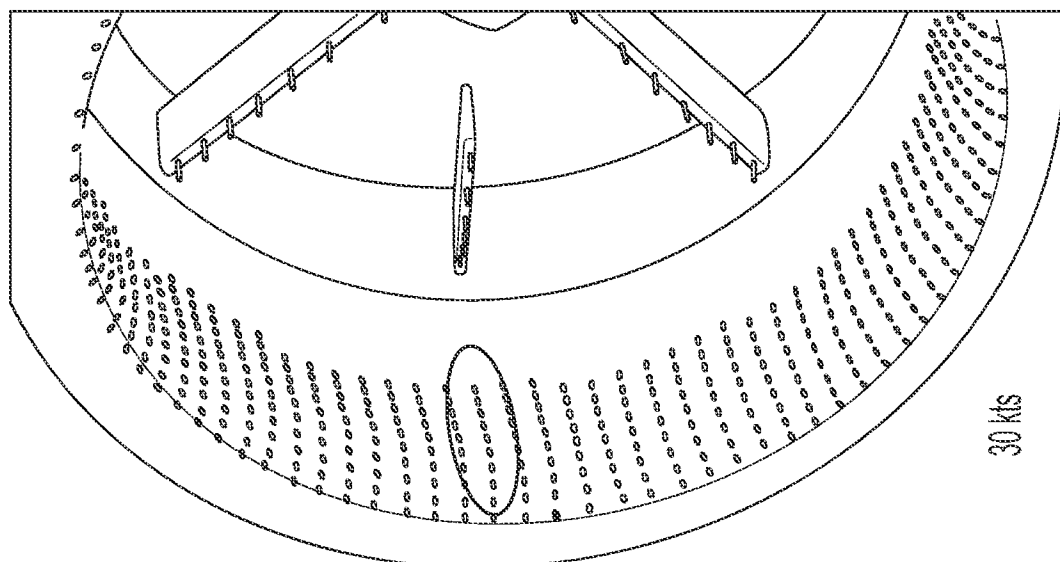
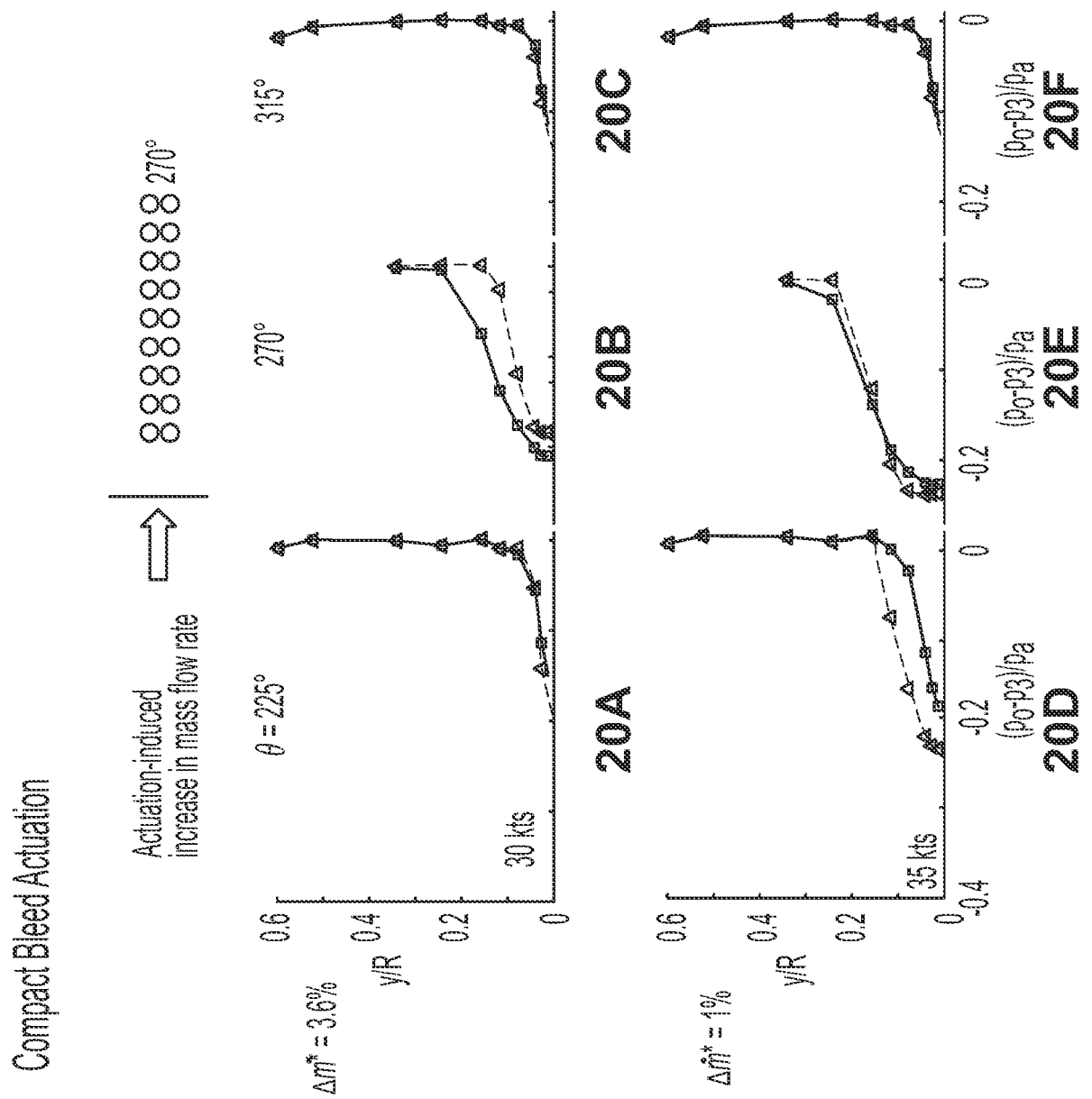


FIG. 20

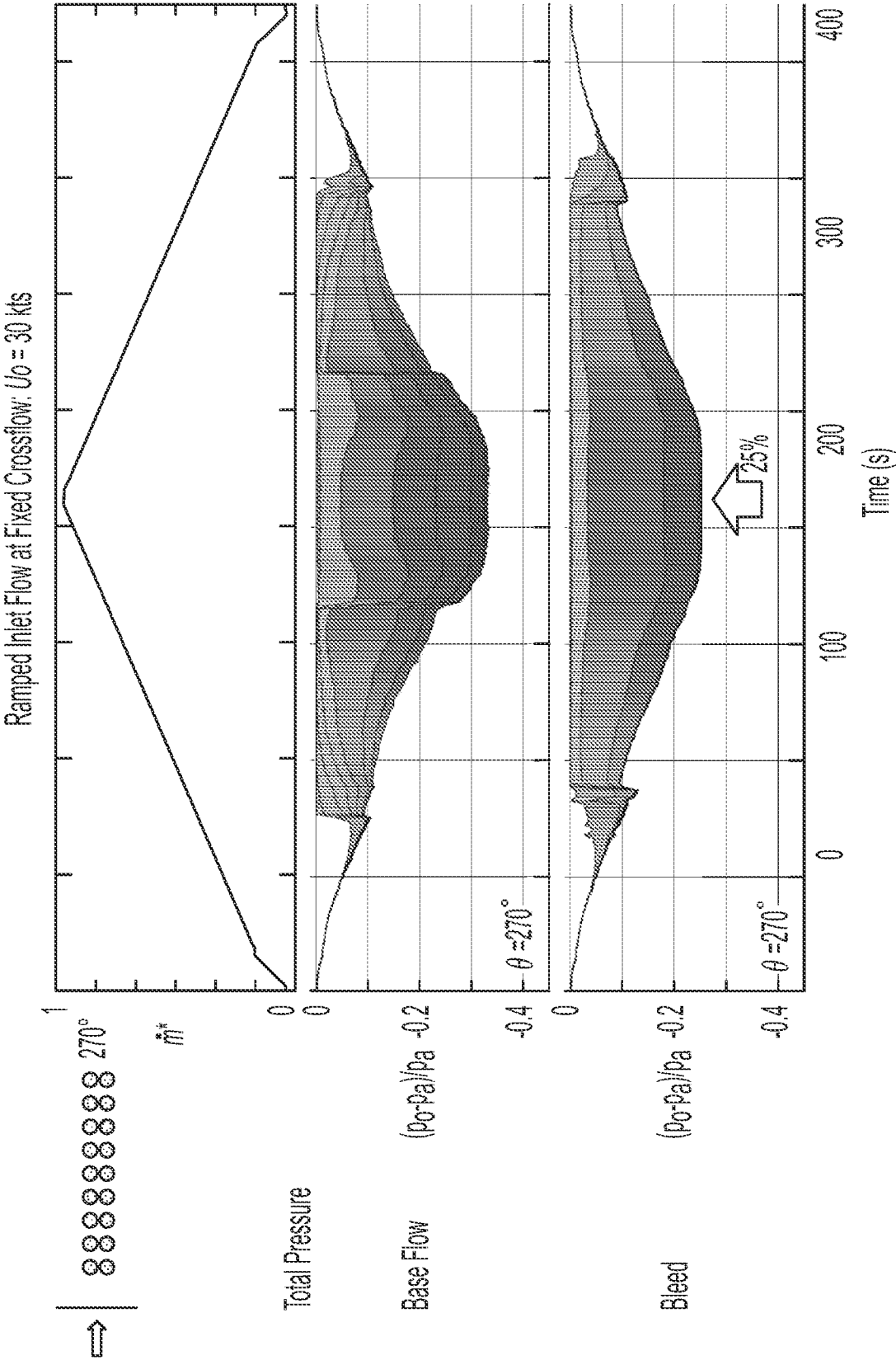


FIG. 21

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2019/063764

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - B64C 21/08; B64C 21/02; B64C 21/04; B64C 21/06; B64D 29/00; B64D 33/02 (2020.01)

CPC - B64C 21/08; B64C 21/025; B64C 2230/04; B64C 2230/06; B64C 2230/20; B64C 2230/22; B64D 2033/0226; F05D 2220/32 (2020.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

USPC - 60/204; 60/230; 244/53B; 244/199.1; 244/204; 244/207; 244/208 (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X ---	US 2017/0001730 A1 (ROLLS-ROYCE PLC) 05 January 2017 (05.01.2017) entire document	6 ---
Y		1-5, 7
X ---	US 2016/0144949 A1 (ROHR, INC.) 26 May 2016 (26.05.2016) entire document	8-12 ---
Y		1-5, 7
A	US 2012/0325978 A1 (JAIN) 27 December 2012 (27.12.2012) entire document	1-12
A	US 2018/0010518 A1 (ROLLS-ROYCE DEUTSCHLAND LTD & CO KG) 11 January 2018 (11.01.2018) entire document	1-12
A	US 2014/0321970 A1 (UNITED TECHNOLOGIES CORPORATION) 30 October 2014 (30.10.2014) entire document	1-12

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

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"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

07 January 2020

Date of mailing of the international search report

06 FEB 2020

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