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CENTRIFUGAL COMPRESSION MACHINERY FOR WET NATURAL GAS APPLICATIONS: PRELIMINARY PERFORMANCE MEASUREMENTS AND A SCHEME TO RECOVER LOST PERFORMANCE

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ABSTRACT

Wet gas compression during upstream production is a major concern for the oil and gas industry, due mainly to the presence of liquid hydrocarbons, as high as 13% by mass fraction in the compressed gas, affecting the system performance. Traditionally, compressors are designed for operation with only dry gas, and hence ingesting a liquid-gas mixture causes the compressor to operate in an off-design condition. The off-design operation with wet gas leads to reduction in efficiency and requires up to two times the power as that of dry compression to maintain the flow and pressure ratio equivalent to dry gas operation [1]. To quantify the effect of wet gas on compressor performance, proper characterization of the flow through the compressor impeller is necessary. Specifically, a quantitative study of the effect of wet gas on compressor aerodynamics is needed. This paper presents an experimental study of wet gas flow around a NACA0012 airfoil using air and water in an open-loop wind tunnel. Airfoil performance is quantified for both dry and wet conditions with lift and drag measurements taken for a range of liquid flow rate and airfoil angles of attack. The wet flow consists of a fairly homogenous mixture of air and water droplets at the blade midspan, where the pressure sensors are located. The results of this work quantify the effects of wet gas reducing the aerodynamic performance. This paper further proposes a solution to mitigate the performance degradation due to wet gas flow. The method involves ejecting pressurized air through holes in the airfoil surface to eliminate the liquid film build up on the airfoil. The gas ejection design offers a possible solution to developing rugged compressors for operation in wet gas conditions. The paper will be of interest to end users and designers of compression machinery for wet gas applications.

INTRODUCTION

The development of reliable and efficient wet gas compression technology is paramount for economical extraction of gas-liquid hydrocarbon mixtures from oil and gas production fields. The gas-liquid hydrocarbon mixture brought to the surface typically consists of up to 5% volume of liquid hydrocarbons (13% liquid by mass fraction), necessitating the separation of liquid phase from gas phase, using scrubbers for instance, followed by the compression of gas and pumping of liquid hydrocarbons. As an alternative to installing gas-liquid separation equipment in sub-sea gas fields and off-shore platforms, a smaller installation footprint can be achieved by allowing the gas-liquid mixture to enter the compressor.

Traditionally, compressors are designed to operate with dry gas. The presence of liquid in the compressor inlet gas flow moves the compressor operation to off-design conditions, leading to a drop in performance and efficiency. From compressor performance data in the literature, it is apparent that the liquid affects the aerodynamic performance of the compressor in the impeller flow path. Therefore, the work in this paper provide a step towards improving the understanding of wet gas aerodynamics, as well as a solution to mitigate the liquid effects in the impeller.

This paper presents pressure and drag force measurements on a NACA0012 airfoil, while air-water mixtures of various rates flow over it. The flow inside a centrifugal compressor is highly complex, and unlike the flow around a symmetric airfoil. Nonetheless, the knowledge gained from the characterization of the effect of two-phase flow on the blade aerodynamics can be later extended to more complex flow phenomena observed in centrifugal compressors. Based on the measurements, a novel scheme of air ejection through airfoil suction and pressure surfaces is proposed to recover the lost aerodynamic performance. The test Reynolds number of 700,000 and liquid mass fractions (LMF=0-15) are consistent with centrifugal compressors in typical oil and gas applications.

REVIEW OF RELEVANT LITERATURE

The relevant literature review is limited to oil and gas applications with centrifugal compressors, the intended application of the results reported in this paper. It is realized that there is much literature on the subject of wet gas compression in axial flow compressors for inlet fogging, overspray, and online water washing. The typical liquid mass fractions (LMF) and droplet sizes for axial compressors are much less than those found in oil and gas applications. Axial compressors typically experience 1% LMF and less than 25 μm droplet sizes [2]; whereas oil and gas applications may experience LMF up to 13% [1] and liquid distributions dictated by the natural flow regime in the well-head piping.

To investigate the effects of wet gas on compressor performance in oil and gas applications, previous experimental studies have used gas-liquid hydrocarbon mixtures [3,4] or air and water at elevated [5,6] or ambient pressure [1,7]. Air and water has been the most common approach for studying wet gas compression effects because of the low cost and safety of testing air-water instead of gas-liquid hydrocarbons. A comparison of test data in the literature shows that compressor performance trends using air and water are similar to hydrocarbon testing for increased power and off-design performance.

Hundseid *et al.* [4] and Brenne *et al.* [3] present single-stage compressor data using gas and liquid hydrocarbons at high pressure (30 bar and 70 bar). Hundseid *et al.* presented an evaluation of the performance data using a polytropic analysis that included the presence of the liquid phase in the bulk fluid properties. It was found that the data scatter of polytropic head and efficiency, correcting for the presence of liquid, increased at high liquid mass fractions. The authors suggest that the scatter is likely due to performance effects of a liquid film in the impeller flow path. Similarly, Brenne *et al.* describes a reduction in compressor efficiency as liquid mass fraction increase, and attributes the cause on the corresponding internal losses in the compressor.

Ransom *et al.* [5] and Bertoneri *et al.* [6] report compressor testing for a two-stage centrifugal compressor ingesting air and water at 20 bar suction pressure. The performance measurements over a range of LMF indicate trends similar to hydrocarbon testing. The authors attribute the presence of the liquid in the flow path as contributing to additional flow losses, in addition to thermodynamic effects of the liquid on compressor performance

Wet gas compressor performance testing by Fabrizzi *et al.* [1] and Grüner *et al.* [7] with air and water at atmospheric suction pressure shows the significance of LMF on compressor performance. Specifically, for small amounts of liquid volume being ingested by the compressor, the corresponding large LMF, due to the large liquid-gas density ratio, produces similar compressor performance trends that are seen at higher pressures. In both studies, the authors conclude the presence of liquid in the impeller flow path contributes to significant performance losses.

Previous literature focusing on multiphase flow around airfoils reveals a reduction in aerodynamic performance due to the presence of a liquid film on the airfoil surface. Specifically, aerodynamic drag increases while lift decreases, which is akin to an increase in flow surface roughness. Grüner *et al.* [8] reports qualitative observations of an air-water mixture flowing across an airfoil in a transparent test section. The authors observe that the liquid film buildup on the airfoil reduce the airfoil performance by causing premature boundary layer separation and altering the inlet flow angle. Earlier studies of airplane wing sections in rain by Hansman and Barsotti [9] and Hansman and Craig [10] quantitatively show an increase in airfoil drag and reduction of airfoil lift due to the presence of water in the flow. The airfoil geometry, angle of attack, and the quantity of water affect the airfoil performance. It is important to note that quantitative measurements of airfoil performance in rain are typically reported for LMF values less than 2% [11].

The work presented in this paper provides quantitative measurements and visual observations of airfoil performance under wet gas conditions with LMF as high as 8%. Airfoil lift and drag forces are measured to characterize a baseline performance. Then, a method using gas ejection to recover airfoil performance under wet gas conditions is tested.

Previous studies of compressor performance [1-7] have noted that there is likely a significant thermodynamic effect of the liquid on compressor performance in the form of heat transfer and phase. The measurements reported in this paper, however, eliminate a significant contribution of thermodynamic effects due to the incompressible and isothermal test conditions in the open loop wind tunnel.

DESCRIPTION OF TEST RIG

An open-loop wind tunnel is used to provide the air and water flow around a NACA 0012 for measurements of airfoil surface pressure distribution and airfoil lift and drag. Airfoil surface pressure is measured at static pressure holes located along the airfoil surface at two span-wise (height) locations. Airfoil lift and drag are measured using deflections of a cantilever beam mounted to the base of the airfoil.

Through the wind tunnel, ambient air flows from left to right in Figure 1, flowing through the inlet section, wind tunnel, transition cone, and finally exiting through the fan. The water supply system (not shown) is completely separate from the wind tunnel. Air flow through the wind tunnel is driven by a 36″ diameter fan with variable blade angle from 30° to 50°, providing up to 45,000 SCFM.

The wind tunnel inlet includes a 100 mm thick honeycomb flow straightener to condition the flow. All sections of the wind tunnel are bolted together with gaskets to reduce flow leakage. The test section that contains the airfoil has a square cross-section measuring 0.53m x 0.53m (21″x21″) All tests are conducted at airfoil chord Reynolds number of 700,000 with an average flow velocity of 45 m/s in the test section. The Reynolds number based on the test section width is 1,400,000, which is consistent with typical flow passage Reynolds numbers in centrifugal compressors [12]. The flow entering the wind tunnel test section is verified to be uniform within 10% of the centerline velocity across the cross-section, as shown in Figure 2. The axial fan downstream of the wind tunnel causes the increasing velocity, moving away from the centerline.

Figure 1. An open-loop wind tunnel is used to measure wet gas aerodynamic performance

The airfoil is located in the center of the test section, 4.5D_h downstream of the wind tunnel inlet section and 4.5D_h upstream of the diffuser section. Transparent, polycarbonate windows are placed at the airfoil location to capture images of the flow around the airfoil, as shown in Figure 3. The airfoil is supported below the test section using a cantilever, the deflections of which aid in the measurement of airfoil lift and drag.

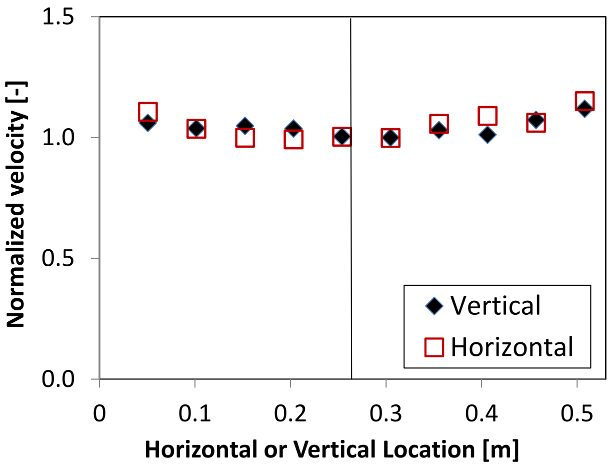

Figure 2. Normalized inlet velocity along the vertical and horizontal directions from the wind tunnel centerline

To provide wet gas flow around the airfoil, water is sprayed onto the airfoil using two nozzles, each with a spray angle of 13°. The nozzles are oriented to provide water coverage of the mid-section of the airfoil with a spray cone diameter of 0.27m (10.5″), and are placed 1.17 m (46”) upstream of the test airfoil leading edge, as shown in **Figure 4.** Water flow rates up to 14% LMF (8gpm) are provided to the nozzles using a 3 hp water pump. The effect of droplet size is not in the scope of this work; however, the nozzle orifice is 2.4mm (0.094″).

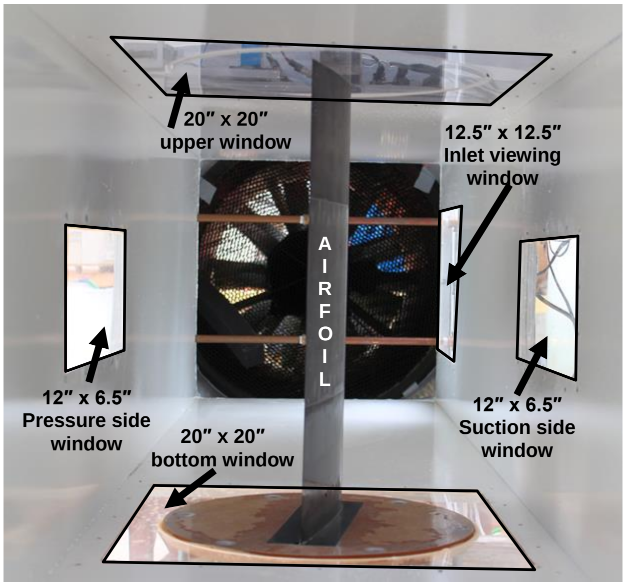

Figure 3. Multiple windows are placed around the airfoil to allow flow visualization

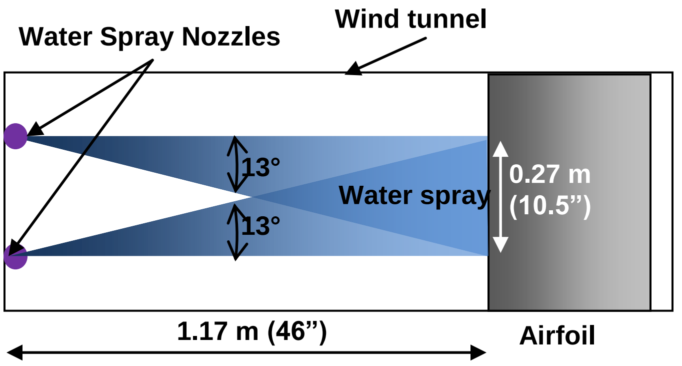

Figure 4. Schematic representation of a wind tunnel section showing the water spray nozzles and spray cone, along with the test airfoil

Airfoil Design

The airfoil geometry studied in this work is NACA 0012, which is a symmetric, two-dimensional airfoil typically used for research studies. Although the airfoil cross-section is a generic shape representative of axial compressor geometry, the effect of a liquid film layer on an aerodynamic surface quantified in this work can be applied to other applications, such as centrifugal compressors. The significance of the current work is in the quantification of performance loss due to wet gas effects.

The airfoil has a chord length of 0.27m (10.5″) and height 0.53m (21″). The airfoil is manufactured of Nylon 6 material using a rapid-prototyping method, and incorporates a steel frame for enhanced structural stiffness. The airfoil consists of three sections and a steel frame, as shown in Figure 5. The steel frame consists of a flat base plate, two vertical beams, and a detachable top plate. The three pieces of the airfoil are installed on the steel frame such that the airfoil’s stiffness is mostly derived from the steel frame. The steel top plate holds the airfoil and the steel frame together with four screws. The base of the steel frame is rigidly attached to the cantilever beam, and can be easily adjusted to change the airfoil angle of attack.

The middle section of the airfoil includes 20 static pressure tap holes (1.67 mm dia.) distributed along the airfoil pressure and suction sides at locations of 0.18m and 0.36m from the wind tunnel floor (40 holes total). For the gas ejection scheme, high-pressure shop air is fed through a passage within the airfoil span to supply air to surface ejection holes. A total of 17 gas ejection holes (3.56mm dia.) are placed 3 hole diameters apart between 0.18m and 0.36m from the wind tunnel floor. The gas ejection holes are placed 17.8 mm downstream of the airfoil leading edge.

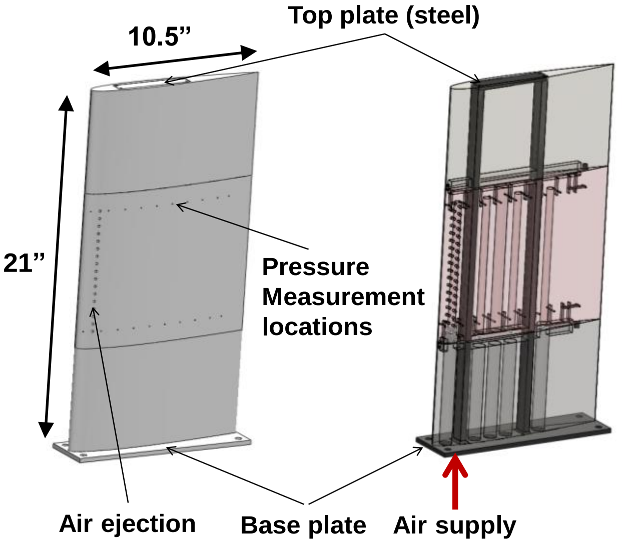

Figure 5. Airfoil Design with an Integral Steel Structural Member for Enhanced Stiffness

MEASUREMENT AND INSTRUMENTATION

A pressure scanner records the differential pressure along the airfoil surface relative to the tunnel inlet total pressure. A total of eight differential pressure transducers are installed in the scanner with an accuracy of ±0.05% of full scale range 2490 Pa (10 in. H_2O). All surface static pressure are measured in reference to the total pressure at the test section inlet using a Pitot tube at the test section center line. Results are reported as pressure coefficient (C_p) with an uncertainty of 0.17%.

The drag forces acting on the airfoil are measured from the deflection of the cantilever beam, using proximity probes, with a maximum error less than 1%. The lift forces are recorded using an analog force gauge with maximum error less than 5%. The accuracy of LMF estimates, based on the measurement uncertainty of the water flow meter, is above 95%.

EXPERIMENTAL RESULTS

The experimental procedure involves measuring the airfoil drag and lift, flow velocity at the wind tunnel inlet, and the pressure distribution on the airfoil surface. Measurements are taken for a chord Re = 700,000, based on dry air, with and without water sprayed into the tunnel. Results being reported are for the middle section of the airfoil subjected to water spray. The lift and drag force on the airfoil in the regions of the airfoil not subjected to water spray are subtracted from the measured value. Additionally, the LMF values reported are calculated from the cross-sectional area of the spray cone at the airfoil (spray cone diameter is 0.27 m). See Table 1 for the test matrix, listing the test parameters and measurements performed.

Table 1. Test parameters and measurements performed

Angle of attack,α	LMF [%]	Air ejection pressure [psi]	Measurements
0	0,4,8,12,15	0,50,100, 140	Pressure, Drag
5	0,4,8,12,15	-	Pressure, Drag, Lift
10	0,4,8,12,15	140	Pressure, Drag, Lift

Dry Gas Experimental Results

Figure 6 depicts the comparison of the analytical predictions and measured pressure coefficients (C_p) on the airfoil surface. Here, X/C = (Distance from airfoil leading edge)/(Airfoil chord length). Note that the maximum range of the pressure transducers is only 0.36 psi. Hence, the pressure measurements close to the leading edge on the suction side, for some angles of attack, are outside this range due to the local separation region.

Analytical predictions of the airfoil pressure coefficient distribution are calculated using an analytical derivation of the flow about a wing section, using information from Abbott and von Doenhoff [1]. The distribution of pressure coefficient along the airfoil surface is provided by Ref. [2] for a NACA 0012.

Wet Gas Experimental Results

This section describes the results for tests with water sprayed on the airfoil during dry air flow. Figure 7 shows the normalized drag coefficients versus LMF values for angles of attack α= 0°, 5°, and 10°. Note that the drag forces are normalized with respect to the drag corresponding to dry air flow, for each angle of attack. The experimental data shows that the drag force increases with LMF, the effect being more pronounced at higher angles of attacks. Figure 8 depicts the decrease in lift with increasing water flow. As in Figure 7 for the drag coefficients, the effect of liquid content in the flow is more pronounced at higher α. Note that lift coefficient for α = 0° is not shown because the NACA 0012 airfoil produces zero lift. As mentioned before, the maximum uncertainty in the drag and lift coefficients are 1% and 5%, respectively. The difference is due to the measurement devices used.

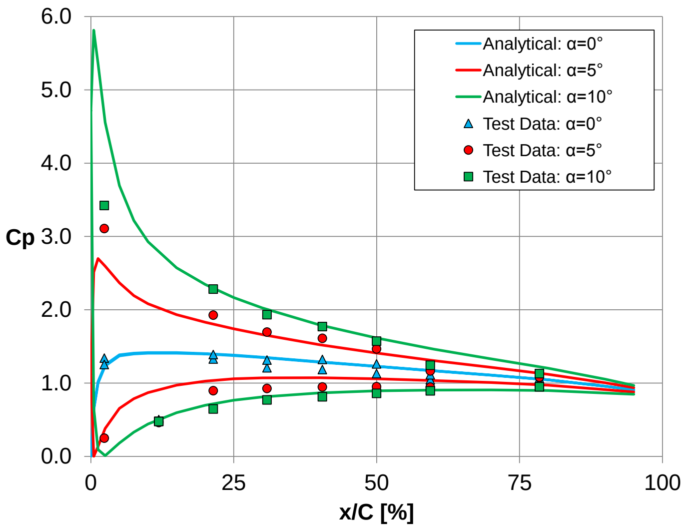

Figure 6. Comparison of predicted and measured pressure coefficient (C_p) along the airfoil surface. Air with no liquid

The measured effect of wet gas on drag is shown to be much greater than the effect on lift. At α = 10° and 15% LMF, drag is measured to be eight times greater than with only air; whereas the lift is measured to be half that with only air. For the case of drag, it is likely that the primary contribution of wet gas is the reduction in boundary layer momentum. Specifically, air loses momentum by accelerating larger water particles on the airfoil surface.

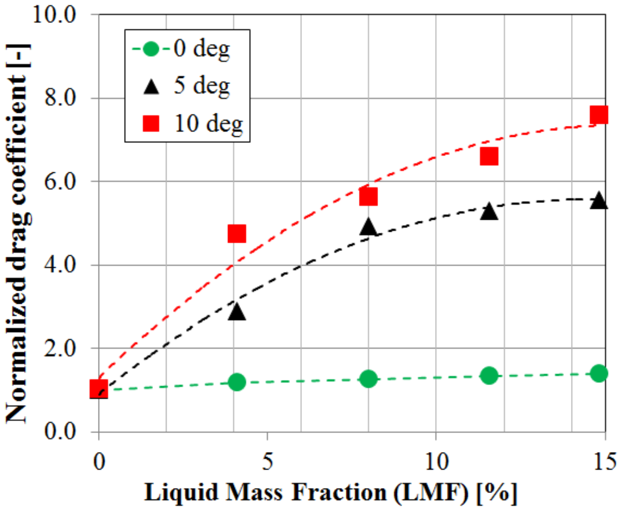

Figure 7. Normalized drag coefficients versus liquid mass fraction (LMF) for various airfoil angles of attacks. Inlet air Re ~ 700,000

Figure 9 shows a photograph of the water film on the suction side of the airfoil operating at α=10° with 10% LMF. The flow of the film in the upstream direction (opposite the air flow) suggests that the water is interacting with the separation region on the suction side of the airfoil. Because the size of the separation region was not measured, it is unknown how the water contributed to increasing size of the separation region. As seen in Figure 9, for 10% LMF, a nearly unbroken film of water is present on the entire airfoil surface. In studies of airplane wings in rain [11,12], however, the liquid film on an airfoil surface is broken into rivulets because the LMF is less than 1%. Saber and El-Genk [14] experimentally found that the liquid film breaks up into thin rivulets when the liquid flow rate decreases below a threshold value required for maintaining a continuous film. The liquid flow rate is determined by the amount of water droplets impinging on the airfoil surface to form the liquid film, which is driven towards the trailing edge by a shear force that increases with the increasing distance from the leading edge and accelerates the water flow.

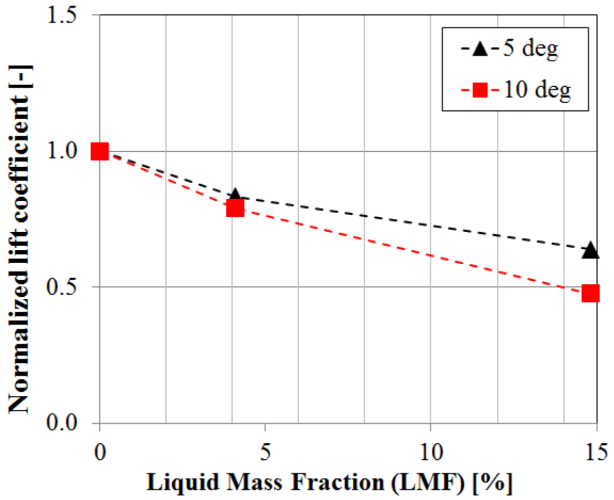

Figure 8. Normalized lift coefficients versus liquid mass fraction (LMF) for various airfoil angles of attacks. Inlet air Re ~ 700,000

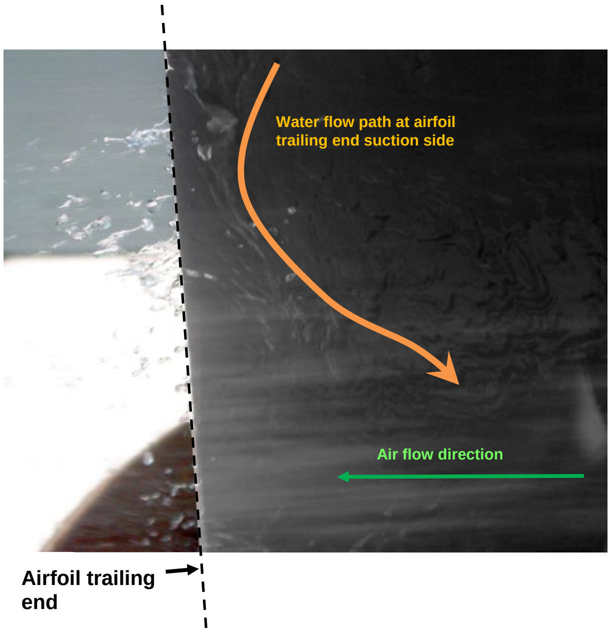

Figure 9. Water flow at the trailing edge suction side of the airfoil for 10 degree angle of attack and 10% LMF

Wet Gas Results: Gas Ejection

The experimental findings show that, with increasing liquid mass fraction (LMF), the drag forces increase while the lift forces decrease. The performance degradation in actual compressors operating in wet conditions, as reported in Ref. [2]

for instance, may be attributed to the influence of liquid droplets on the aerodynamic effect. To reduce the wet airfoil drag coefficient and flow reversal at the trailing edges, the airfoil surface must be kept dry. This paper proposes a scheme of air ejection through the airfoil surface, as depicted in Figure 9, to keep the surface dry, and thus improve the drag and lift characteristics. As the aim of the experiment is to estimate the effect of air ejection on the airfoil lift and drag, and not developing an optimum design, currently the pressurized air is ejected through only one row of holes 17.8 mm from the leading edge on both the pressure side and suction side of the airfoil. The axis for all holes is perpendicular to the airfoil surface.

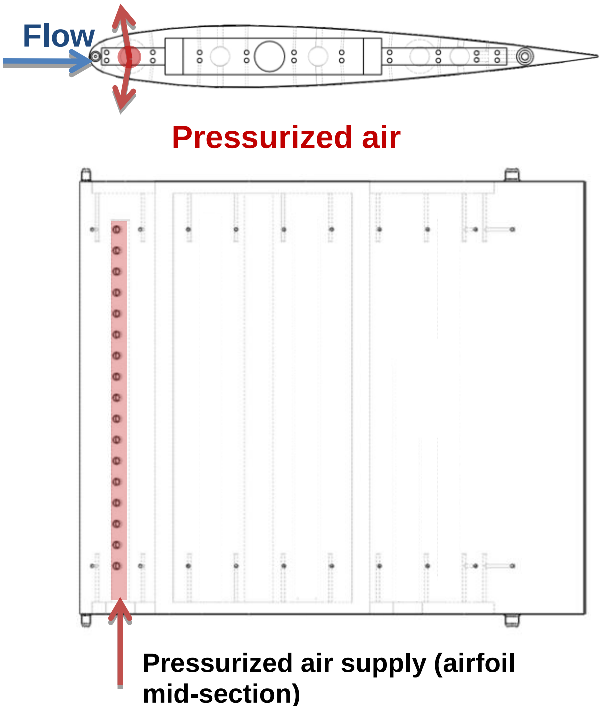

Figure 10. Pressurized air ejected through airfoil mid-section pressure and suction surfaces. Modified airfoil design

Figure 11 shows the photograph of the airfoil surface near the leading edge, with α=0°, LMF=15%, and for the conditions of no air ejection and air ejection at 30 psi. The pressurized air prevents water droplets from impinging on the airfoil surface around and behind the hole. Multiple, and staggered, rows of air ejection holes on the airfoil surface may show more effectiveness in keeping the surfaces dry. Nonetheless, the current findings indicate that any scheme to avoid airfoil surface wetting can improve the lift and drag characteristics.

Figure 12 shows the normalized drag forces, for α = 0°, for a baseline case (air ejection holes covered), and for air ejection holes exposed and air supplied at 0, 50, 100, and 140 psi. The measurements show that the drag coefficients drop when air is ejected through the surfaces. However, the increase in air pressure from 50 psi to 140 psi does not reduce the drag coefficients further. The findings indicate that a minimum air flow pressure exists, for any airfoil angle of attack, beyond which any additional supply pressure does not contribute to performance improvement. The measured drag coefficients with α = 10°, as depicted in Figure 13, also show a beneficial effect of pressurized air supply. The air ejection normal to the suction and pressure surfaces prevents the ingress of liquid into the boundary layer and from wetting the surfaces. This effect, however, is noticeable only in the immediate vicinity of the air ejection holes.

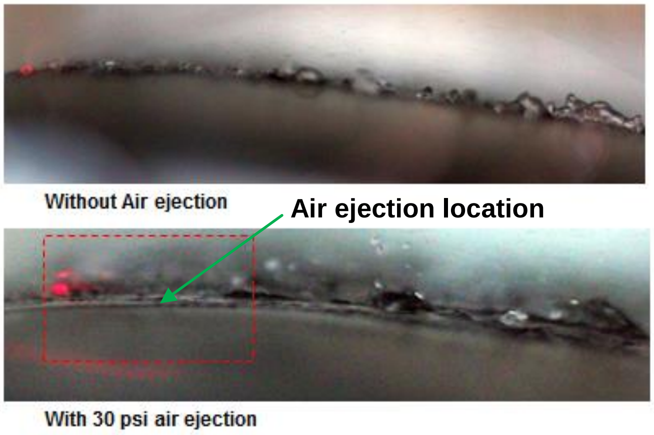

Figure 11. Photographs of airfoil surface, at α=0, with and without air ejection. LMF =15%. Highlighted region shows air ejection location and absence of water droplets on airfoil surface

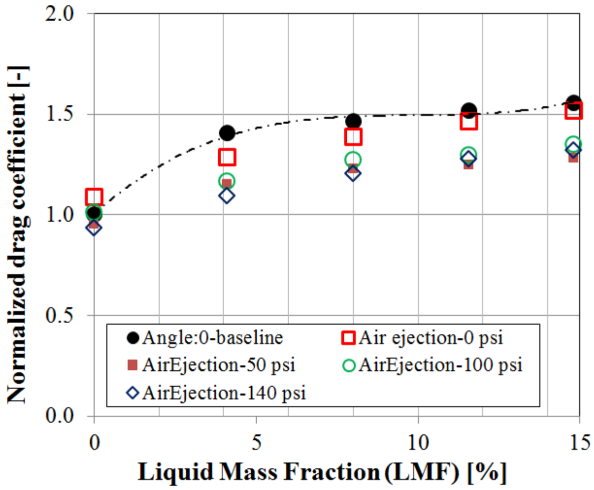

Figure 12. Normalized drag coefficients versus liquid mass fraction (LMF), with and without air ejection, for α=0. Inlet air Re ~ 700,000

Recent experiments at the authors' laboratory [15], in a single stage centrifugal compressor not originally designed to operate in wet conditions, show higher pressure ratios with increasing LVF at comparatively lower flow rates. This phenomenon is thought to be due to a combination of higher density of the fluid and the apparent cooling effect of water on the impellers. However, with increasing flow rates, the liquid presence causes larger losses, and results in a drop in the pressure ratio. Interestingly, the impeller pressure ratio characteristics differed from flange-to-flange characteristics, indicating that the losses in the diffuser and diaphragm are also important. Thus the experimental test results in Ref. [15] corroborate that the presence of liquid causes an apparent increase in frictional losses, in both axial and centrifugal machinery. Further study is required, however, to develop empirical relationship for frictional losses, LMF ratios, flow Reynolds number, and compressor geometry.

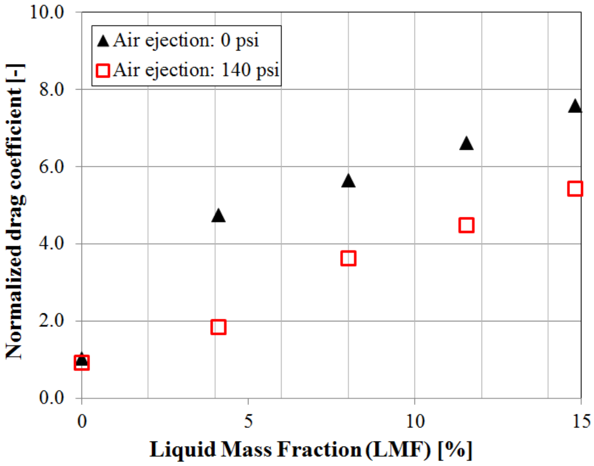

Figure 13. Normalized drag coefficients versus liquid mass fraction (LMF), with and without air ejection, for α=10°.

CONCLUSIONS

Compressors designed to operate with dry gas are capable of operating with limited quantity of atomized fluid particles. However, for applications such as in upstream natural gas production, the gas-liquid mixture may contain as much as 13% by mass of liquid. The liquid flowing in to a compressor stage will impinge on the blades and generate a thin film of liquid over the pressure and suction surfaces, effectively modifying the blade geometry and surface friction coefficient. Wet gas operation drives the compressor to off-design conditions, and most often leads to lower efficiency.

This paper details the construction of a test rig to measure the dynamic pressure distribution and drag coefficients in a NACA0012 airfoil of chord length 0.27 m, at Re = 700,000. The flow conditions are varied by spraying water into the air flow to attain liquid mass fractions (LMF) of up to 15%, while the airfoil angles of attack varies ($0° \le \alpha \le 10°$). The measured pressure coefficients for dry air agree well with established airfoil theory. The water flow over the airfoil surfaces indicates reversal of flow, especially near the trailing edge. With increasing LMF, the airfoil drag increases up to 8 times the dry air drag value while lift decreases by as much as 50% of the dry air value, indicating that the aerodynamic performance degradation is non-negligible for wet gas compression.

It is important to recall that much of the wet gas compressor testing in the literature points to thermodynamic effects playing a significant role in performance degradation. The results of this work, however, illustrate that the degradation is strongly influenced by aerodynamic effects. Specifically, the open-loop wind tunnel testing effectively eliminates thermodynamic effects because of the incompressible, isothermal conditions in which testing was conducted. Considering the case of the 50% decrease in lift coefficient, measured in this work for operations with 15 % LMF, a compressor operating with similar LMF ratios is likely to operate with lower throughput, or require more power to match the original output.

This paper proposes a solution to reduce the drag due to liquid flow on the airfoil by ejecting pressurized air through the airfoil suction and pressure surfaces. Air ejection through the surfaces effectively reduces drag for test LMF values as much as 15%. The air ejection normal to the surface prevents the water droplet ingress into the boundary layer, thus reducing the loss in boundary layer momentum arising from liquid entrainment, and improves the aerodynamic performance. For the gas ejection method to be implemented in a compressor, a thorough design-study would be required to determine the parameters of the gas ejection design to improve aerodynamic performance without sacrificing compressor efficiency.

The findings of this work are specific to a NACA0012 airfoil cross-section and the fundamental aerodynamic effects of wet gas can be applied to other airfoil cross-sections. Future work must focus of studying other airfoil cross-section shapes to determine the sensitivity of cross-section shape to wet gas aerodynamic influence. As seen in studies of airplane wings in rain, some airfoil shapes perform better than others in a rain environment; however, the underlying cause for better performance is not known.

ACKNOWLEDGEMENTS

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NOMENCLATURE

C	airfoil chord length [m]
C_p	pressure coefficient, $Cp=(Pt-P)/0.5\rho U_\infty^2$
D	air ejection hole diameter
D_h	hydraulic diameter
LMF	liquid mass fraction, LMF = $\dot{m}_\ell / (\dot{m}_\ell + \dot{m}_g)$
$\dot{m}$	mass flow rate
P	static pressure [Pa]
Re	airfoil Reynolds number, $Re = \rho U_\infty C / \mu$
U_∞	free stream velocity [m/s]
X	distance from airfoil leading edge [m]

Greek

α	airfoil angle of attack with respect to free stream flow direction [deg]
μ	dynamic viscosity [kg/m/s]
ρ	gas density [kg/m3]

Subscripts

ℓ	liquid
g	gas
T	total pressure

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