GAS TURBINE BLADE LEADING EDGE PROFILE EFFECT ON FILM COOLING EFFECTIVENESS USING PSP TECHNIQUE

A Thesis

by

SHAMSUL ARFIN QURESHI

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Chair of Committee,	Je Chin Han
Committee Members,	Hamn-Ching Chen
	Partha Mukherjee
Head of Department,	Andreas A. Polycarpou

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ABSTRACT

A detailed study of various geometric & flow parameters that influence the film cooling effectiveness of gas turbine blade leading edge region was carried out. The parameters studied include leading edge shape, effect of gill holes, internal impingement, coolant to main stream density ratio & blowing ratio. Three leading edges which include a cylindrical leading edge of radius R = 38.1 mm, elliptical leading edge of major radius 1.5 R & elliptical leading edge of major radius 2 R have been studied. All three leading edges have cylindrical coolant holes at α 25°, β 0° & gill holes at alpha 0°, β 30°. There are three rows of film cooling holes with 15 holes each at fixed pitch of 4D 0° & ±30° & two rows of gill holes at ±60° when measured from inside surface. Row spacing in elliptical leading edges has kept at same arc length as in cylindrical leading edge instead of angle. A provision for internal impingement at stagnation region has also been provided, impingement plate has been kept at fixed distance of 31.7 mm from stagnation point in all three leading edges. Film Cooling Effectiveness on leading edge surface has been measured using Pressure Sensitive Paint (PSP).

Results obtained in case of the cylindrical leading edge are in agreement with the previous results available in open literature, however results of 1.5 R & 2 R are new & not much is available in open literature about elliptical shaped leading edges. In general 1.5 R leading edge has shown best performance & 2 R the worst. Interesting observations have also been made regarding the effect of gill holes & internal impingement.

ACKNOWLEDGEMENTS

I am extremely grateful for the support & guidance of my committee chair Dr. J.C Han, without his support this work could not have been completed. I would also like to thank Dr. Mukherjee & Dr. Chen for their support & service as my thesis committee members.

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NOMENCLATURE

α	Axial angle to the mainstream
β	Compound angle to the mainstream
η	Film cooling effectiveness
ρ	Density, kg/m3
C	Mass fraction
D	Diameter of film cooling hole
DR	Coolant to mainstream density ratio
I	PSP emission intensity
L/D	Injection hole length to diameter ratio
M	Blowing ratio/ Mass flux ratio
MFR	Coolant to mainstream mass flow rate
P/D	hole spacing to diameter ratio
T	Temperature
Tu	Turbulence intensity

Subscript

∞	Mainstream property air Property with air injection
Aw	Adiabatic wall
Blk	Black condition
C	Coolant

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1. INTRODUCTION

Gas turbine technology cannot proceed any further without advancement in its blade/vane cooling technology. Turbine efficiency is enhanced by increasing its (RIT) rotor inlet temperature, which has reached up to 2500 ˚F & could raise up to 3500 ˚F in near future [1]. This temperature far exceeds material's melting point, hence the only reason why gas turbines have come this far is the advancement in its cooling technology. Turbine blade cooling is divided in two parts which are internal cooling & external cooling of the blade/vane. Internal cooling techniques include impingement, pin-fins, rib-turbulated cooling & external cooling is achieved by making a coolant film over the surface. Film cooling is achieved by inducing coolant through film cooling holes situated on outer surface of blade. Film cooling effectiveness is the measure of how good the cooling works.

Film cooling becomes even more critical on the blade leading edge portion where maximum heat transfer occurs because of stagnation. In this study effect of both geometric & flow parameters will be assessed. Geometric parameters include effect of changing leading edge profile, effect of gill holes & effect of internal impingement on external film cooling effectiveness. Flow parameters include effect of Density ratio & Blowing ratio. Measurement technique to be used is (PSP) Pressure Sensitive Paint which is a mass transfer technique.

1.1 Film cooling

Gas turbine blades are cooled internally and externally. Internal cooling is achieved by passing the coolant through several enhanced serpentine passages inside the blades and extracting the heat from the outside of the blades [1]. External cooling is also called film cooling. Internal coolant air is ejected out through discrete holes or slots to provide a coolant film to protect the outside surface of the blade from hot combustion gases [1]. Coolant film serves as a barrier between hot mainstream & the blade. Highest effectiveness is observed right at the downstream of coolant holes & a decline is observed further downstream. Hence to achieve better effectiveness numerous coolant hole rows are provided starting from stagnation & down along the span of blade.

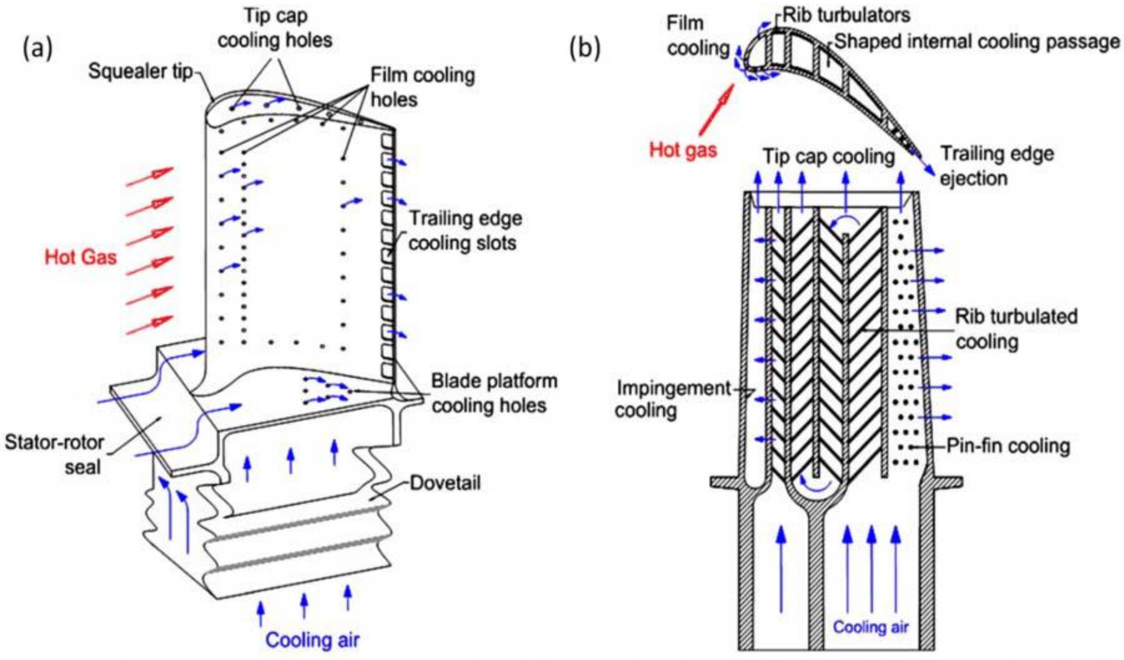

Figure 1: Schematic of blade cooling (a) Film cooling (b) Internal cooling [1]

Figure 1 shows cooling arrangement of both internal and external cooling. Coolant air is a precious commodity in gas turbine since it effect the thermal efficiency of the turbine, hence precise calculation of the coolant to be used & an efficient coolant delivery design is very important. Parameters such as hole shape, length, row spacing, pitch & thickness of blade wall at stagnation & other regions highly influences the cooling performance of a blade.

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2 LITERATURE REVIEW

2.1 Effect of blowing ratio

Blowing ratio (M) is the ratio of coolant mass flux to that of mainstream. Film cooling effectiveness has generally been observed to increase with increasing blowing ratio, however in case of leading edge the effect is different in stagnation region & the first cooling hole row at ±30°. Also it is interesting to see the effect of gill holes on overall film cooling. As per Falcoz et al [2] at blowing ratio higher than M 1.76 coolant lift-off comes in to play & increasing blowing ratio may not have the desired effect afterwards. However this study only deals with blowing ratios 0.5, 1.0 & 1.5 hence the tipping point has not been observed & for the given range increasing blowing ratio has a positive impact. Similar results are discussed by Li et al [3] & Ou et al [4].

2.2 Effect of density ratio

Density ratio is the ratio of coolant density to mainstream density. Film cooling effectiveness depends heavily on Density Ratio of coolant. In most gas turbines, typical coolant density ratio is kept at 1.7 to 2.0 [1]. Temperature difference between coolant & mainstream causes the density difference. At a given M, film cooling effectiveness is directly proportional to DR, however at higher DR & lower M the effect can be reverted in case of leading edge. In some cases even complete shutoff of coolant to stagnation region has also been observed. Similar results are reported by Li et al [3], Gao et al [5] & Salcudean et al [6].

2.3 Effect of leading edge profile

Effect of showerhead profile shape has not been studied much & very few references are available in open literature, hence the differences between the film cooling effectiveness of the three different shaped leading edges is a new study. Effect of radius is discussed by Ou et al [4].

2.4 Effect of gill holes

Addition of gill holes drawing coolant from the same plenum will be an interesting parameter to study. Since Gill Holes are closer to the relatively flatter end of the blade & are at lesser angle to the mainstream, they are expected to draw more coolant flow compared to the desired evenly distributed local blowing ratio. This effect can be confirmed by measuring local blowing ratio on each cooling hole row & their respective Discharge Coefficients. Row-wise blowing ratio difference has been studied by Ou et al [4] & Nivarthi et al [7].

2.5 Effect of internal impingement

Impingement is employed to improve internal cooling at stagnation region, however its effects on the external film cooling effectiveness is a new parameter to study. Most the information available in open literature deals with impingement separately & its effect on outside film cooling is rarely discussed. Effect of internal impingement is discussed by Nivarthi et al [7]

3 RESEARCH OBJECTIVE

Primary objective of this research is to gather a comprehensive data on the effect of leading edge profile's changing radius, effect of Gill Holes, effect of Internal Impingement & effect of Density & Blowing ratio, all combined together. Test has been performed on three leading edges which include a cylindrical leading edge of radius (R) 38.1 mm, the other leading edges are of radius 1.5 R elliptical & 2 R elliptical, all leading edges have cylindrical cooling holes. Table 1 contains the details of leading edge design.

	1R	**1.5R**	**2R**
Height	247.5 mm	247.5 mm	247.5 mm
Radius	38.1 mm	57.15 mm	76.2 mm
Thickness	6.4 mm	6.4 mm	6.4 mm
Film hole diameter	3.2 mm	3.2 mm	3.2 mm
Alpha (α)	25º	25º	25º
Beta (β)	0º	0º	0º
Film hole pitch (4D)	12.8 mm	12.8 mm	12.8 mm
No. of film hole rows	3	3	3
* Row spacing (along curve)	19.95 mm	19.95 mm	19.95 mm
Impingement plate to stagnation row space (z)	31.7 mm	31.7 mm	31.7 mm
Impingement hole diameter (d)	6.2 mm	6.2 mm	6.2 mm
z/d	5.11	5.11	5.11
Impingement plate thickness (t)	9.525 mm	9.525 mm	9.525 mm
t/d	1.536	1.536	1.536
Gill hole dia	3.2 mm	3.2 mm	3.2 mm
Number of gill hole rows	2	2	2
Number of gill holes in each row	15	15	15
Gill hole row pitch	12.8 mm	12.8 mm	12.8 mm

Distance from nearest film cooling hole row	19.939 mm	19.939 mm	19.939 mm

Table 1: Leading edge design details

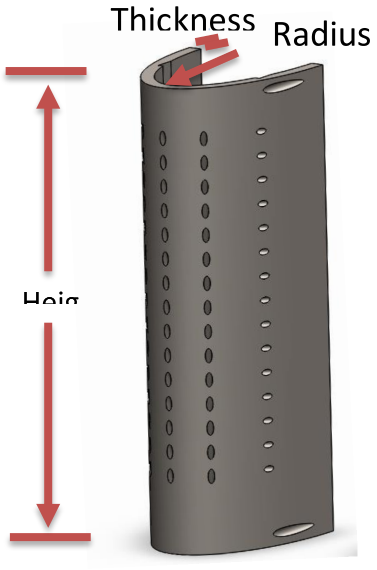

Figure 2: 2 R leading edge with gill holes

3.1 Test Matrix

Leading Edges	Coolant flow arrangements	Density Ratios	Blowing Ratios
- 1R Cylindrical holes - 1.5R Cylindrical holes - 2R Cylindrical holes	- Impingement OFF Gill Hole OFF - Impingement OFF Gill Hole ON - Impingement ON Gill Hole OFF - Impingement ON Gill Hole ON	- 1.0 (Nitrogen) - 1.5 (Carbon Dioxide) - 2.0 (85% Argon & 15% SF6)	- 0.5 - 1.0 - 1.5

Table 2: Test matrix

Table 2 summarizes all the tests that have been performed. Figure 3 shows all possible coolant inlet arrangements

Total number of test cases	**108**
Cases per leading edge	**36**

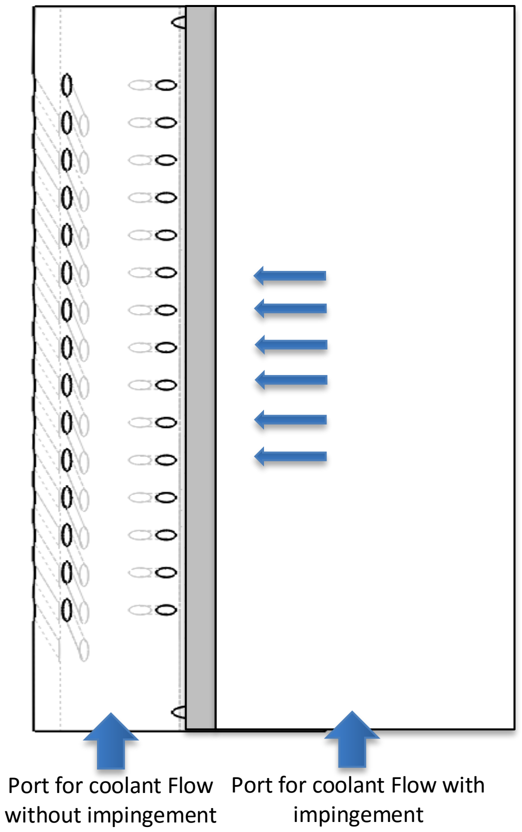

Figure 3: Coolant inlet arrangements

4 INSTRUMENTATION & MEASUREMENT METHOD

4.1 Instrumentation

Experiments have been carried out in the test section of a low speed suction type wind tunnel at a mainstream velocity of 20.89 m/s & a corresponding Reynold's number 102,446. The cross-section of the test channel is 76.2 cm (30") by 25.4 cm (10"). An Induction fan on the downstream is employed to create mainstream flow.

The leading edge is placed 76.2 cm (30") downstream of the turbulence grid which is made of ½" thick bars. It is designed in such a way that the stagnation point of all three leading edges is exactly at the same distance from turbulence grid no matter what the radius may be. Figure 4 shows complete experimental setup of the wind tunnel.

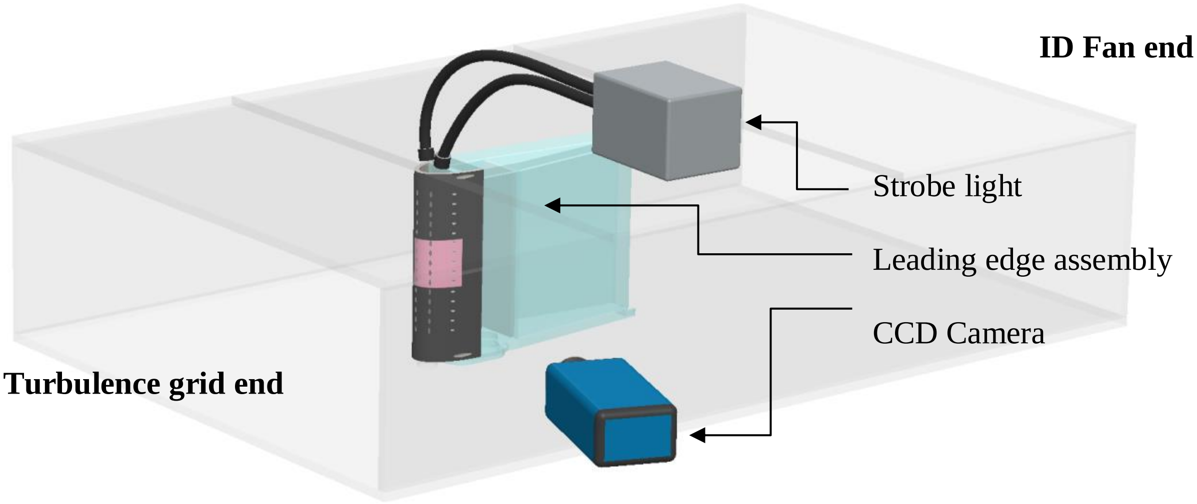

Figure 4: Complete experimental setup

Coolants supply is by gas cylinders (N2, CO2, and mixture) & an air compressor. The coolant flow rate is measured and controlled by Dwyer rotameters. Mainstream velocity is measured by a Pitot-static tube connected to a micro-manometer. A fixed turbulence grid with turbulence intensity of 7% is used. Figure 5 is an exploded view of the leading edge test rig assembly.

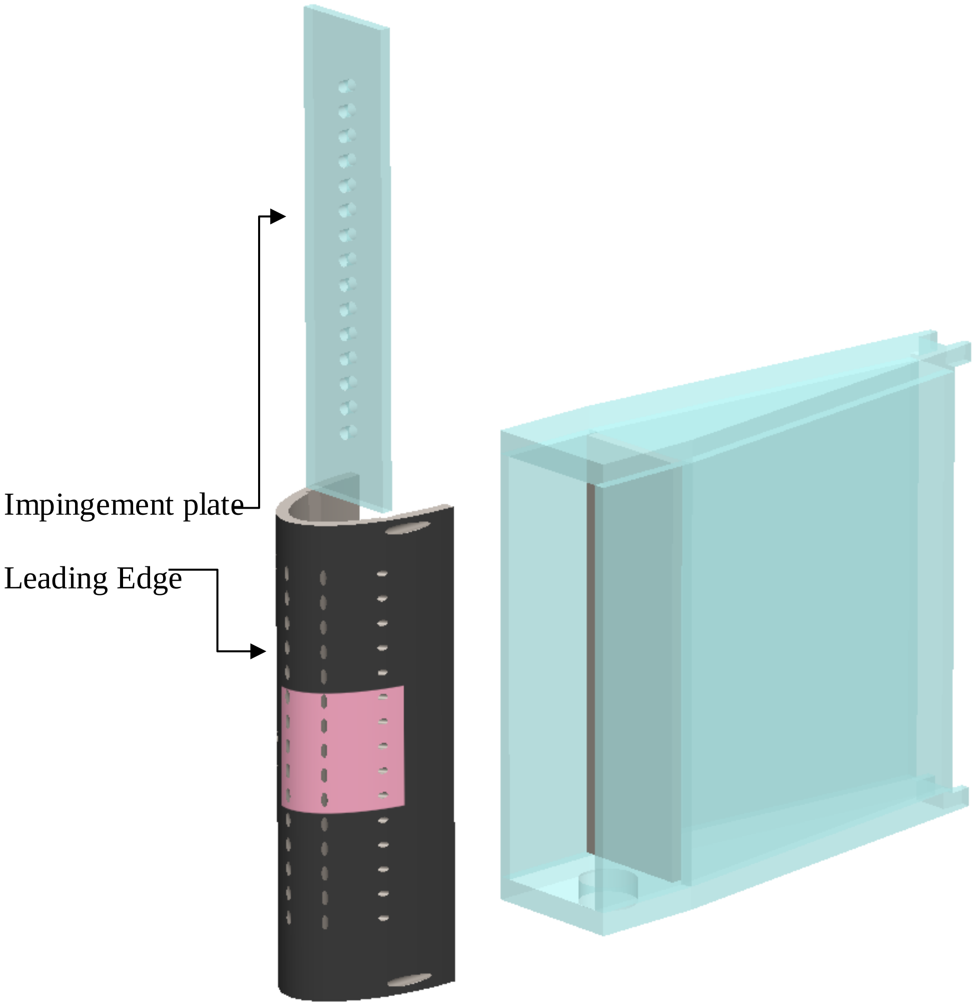

Figure 5: Leading edge assembly exploded view

Figure 6 shows all three leading edges with region of interest (ROI) painted with PSP.

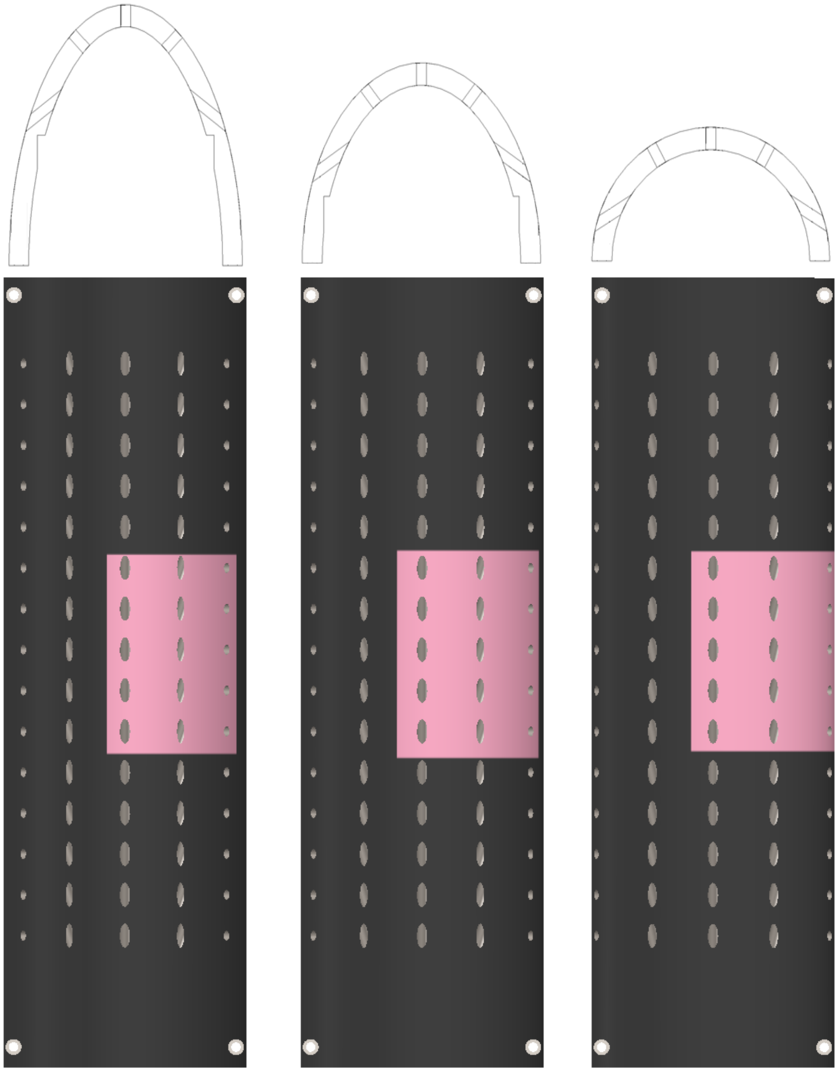

Figure 6: Region of interest

4.2 Pressure sensitive paint technique

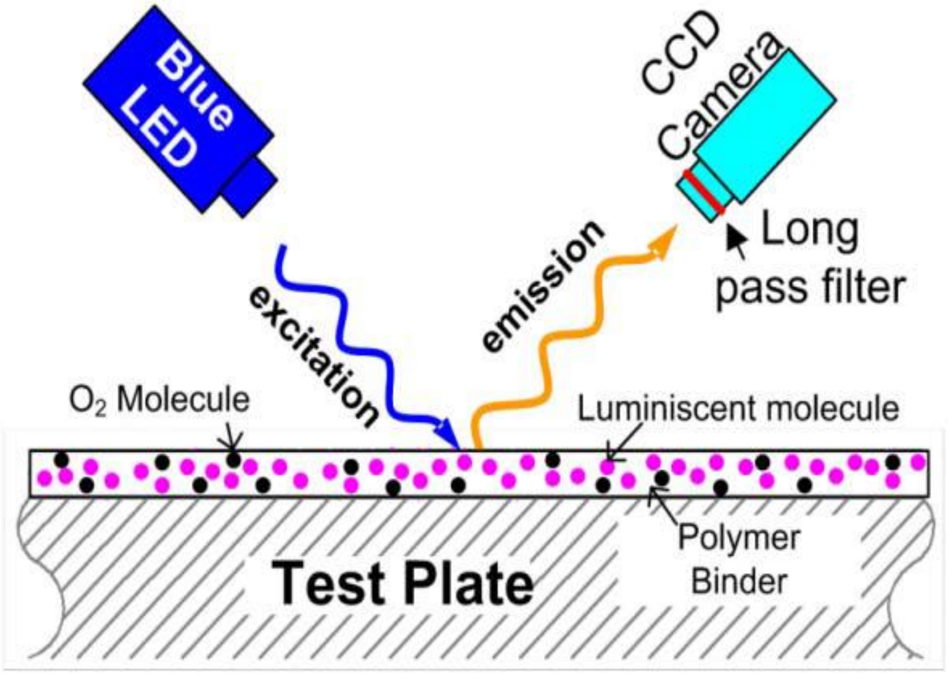

Figure 7: Schematic of PSP paint principle [3]

Figure 7 shows schematic of PSP principle. Measurement technique to be used is (PSP) Pressure Sensitive Paint which is a mass transfer technique. PSP is a non-intrusive technique with high spatial resolution compared to conventional methods. It was introduced first by Zhang, Li et al. [3] for film cooling effectiveness measurement, before that it was solely used in aerodynamic studies to measure surface pressure. PSP consists of fluorescent molecules and oxygen-permeable polymer binder, which works on the principle of oxygen quenching. A 650 nm strobe light will be used to excite the fluorescent molecules. After excitation & fluorescent molecules emit light inversely proportional to the partial pressure of oxygen in the surrounding. This emitted light is captured in terms of intensity by the CCD camera with long pass filter. This captured intensity is calibrated with partial pressure of oxygen & the correlation generated gives partial pressure of oxygen.

Calibration is done using a vacuum chamber with transparent Plexiglas top & the same light source as being used in experiment. Following are the steps of calibration,

- Paint a small test section with black paint followed by PSP
- Place inside the calibration block and tighten bolts to ensure 100% sealing
- Place beneath a CCD camera and LED light source. Make sure the camera / LED distance and angle is similar to actual test set up.
- Switch on vacuum pump to attain oxygen quenched environment. Take a picture and repeat the step for a wide range of vacuum pressures covering the intensity values expected in the experiment itself.
- Take a reference reading (ambient pressure, light on) and black reading (ambient pressure, light off condition). This is required to normalize intensity and cancel camera noise.
- Plot $\frac{I-I_b}{I_{ref}-I_b}$ versus $\frac{P}{P_{ref}}$

Following formula is used to measure film cooling effectiveness.

$$\eta = \frac{P_{O_2 air} - P_{O_2 mix}}{P_{O_2 air}} = 1 - \frac{1}{\left(\frac{P_{O_2 air}}{P_{O_2 mix}} - 1\right) * W_{mix}/W_{air} + 1}$$

5 RESULTS

5.1 Effect of blowing ratio (M)

For a given density ratio overall effectiveness has been observed to increase with increasing blowing ratio. Each setup has been tested at three blowing ratios, which are 0.5, 1.0 & 1.5 at any given Density ratio. Change in effectiveness observed between M 0.5 & M 1.0 is the highest, because in most cases Higher outside pressure in the stagnation region allows very little or no coolant to come out at M 0.5, however the situation is dramatically improved at M 1.0. Change in effectiveness between M 1.0 & M 1.5 is not as much as between M 0.5 & M 1.0, similar behavior has been reported by Gao et al. [5], it is reported that coolant lift off occurs after M 1.76, which reduces the overall effectiveness [6]. Figure 8 shows effect of increasing blowing ratio.

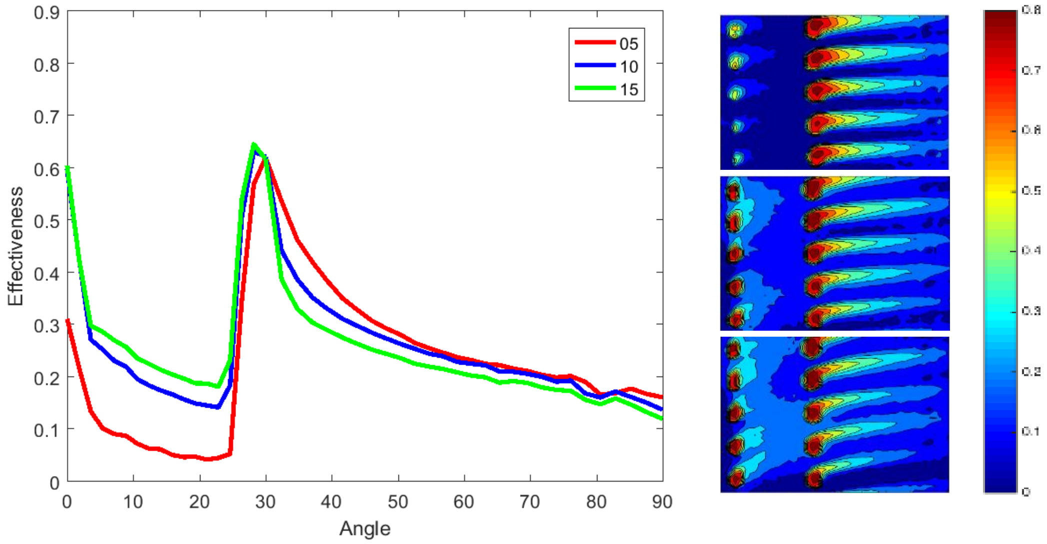

Figure 8: 1 R Imp OFF GH OFF DR 1.5 Blowing ratio comparison

5.2 Effect of density ratio

Each case has been tested at three density ratios which are DR 1.0 (N_2), DR 1.5 (CO_2) & DR 2.0 (85% Ar & 15% SF_6). K type cylinders provided by Praxair have been used for coolant supply. Increasing coolant density ratio has been generally seen to improve film cooling effectiveness. In real gas turbine applications density ratio varies between 1.7 & 2.0 [1] which is achieved by the difference of temperature between the two streams. Effect of density ratio is visible with increasing blowing ratio. At M 0.5 the effectiveness is in the order of DR 1.0, DR 1.5 & DR 2.0, whereas at M 1.0 & above the order is inverted & coolant with higher DR gives better effectiveness. Similar behavior has also been reported by Li et al [3] & Gao et al [5]. Figure 9 shows effect of increasing density ratio.

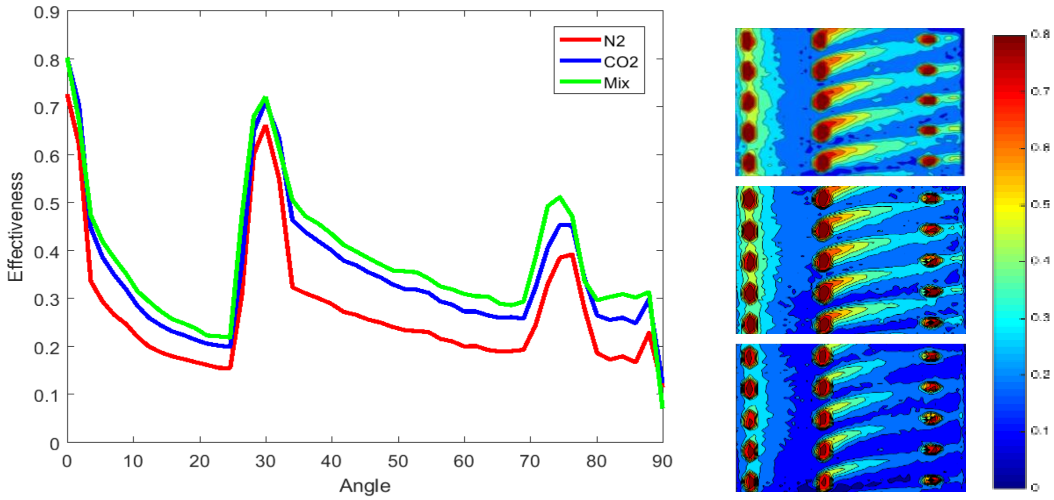

Figure 9: 1.5 R Imp ON GH ON M 1.5 Density ratio comparison

5.3 Effect of leading edge profile shape

Effect of leading edge profile on film cooling effectiveness has not been studied much & most studies consider leading edge as a semi cylinder, however this study deals with three leading edges of different profiles. Overall effectiveness has been seen to reduce with increasing profile radius. Same phenomenon has been reported by Falcoz et al [2]. Because of change in profile outside pressure for each leading edge is different which impacts the effectiveness. From the results it can be seen that overall highest effectiveness has been observed in 1.5 R leading edge followed by 1 R & 2 R, hence optimum profile radius for given conditions is in between 1 R & 1.5 R. Figure 10 shows effect of changing leading edge profile.

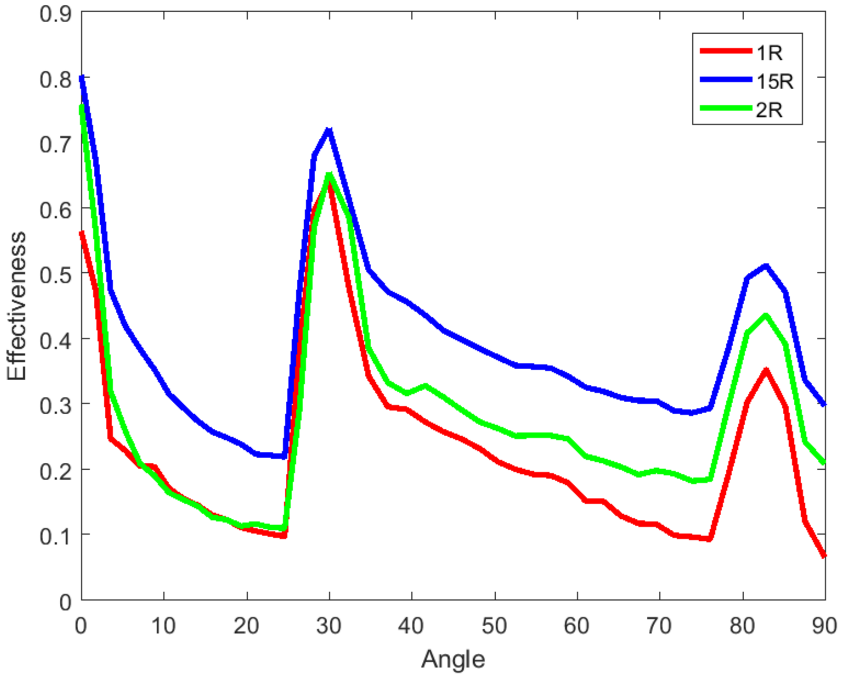

Figure 10: Imp ON GH ON DR 2.0 M 1.5 leading edge profile effect

5.4 Effect of gill holes

Gill holes owing to lower outside pressure draw more coolant than desired, hence at lower blowing ratio (M 0.5) in some cases complete coolant shutoff at stagnation has also been observed, this could seriously endanger the health of blade. Similar phenomenon has also been reported by Salcudean et al [6] & also visible in results of Li et al [3] & Gao et al [5]. However at M 1.0 & M 1.5 stagnation region receives adequate amount of coolant. Figure 11 and 12 show the difference of effectiveness with and without gill holes.

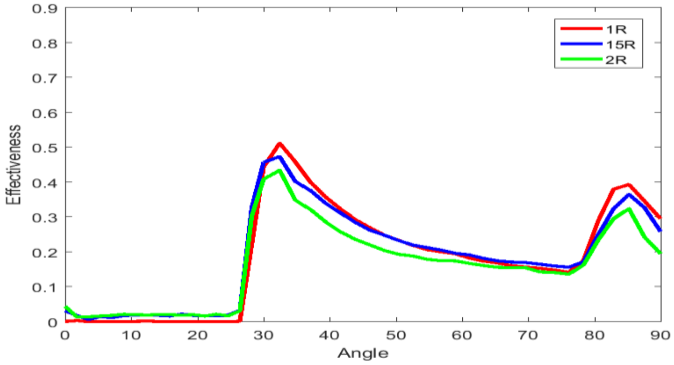

Figure 11: Imp OFF GH ON M 0.5 DR 1.0

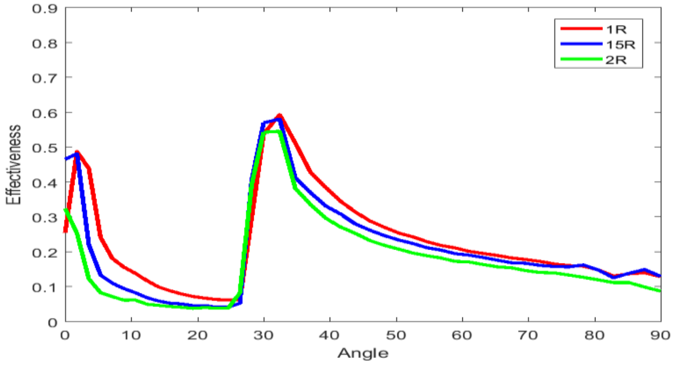

Figure 12: Imp OFF GH OFF M 0.5 DR 1.0

5.5 Effect of internal impingement

True effect of internal impingement can only be seen if a heat transfer study of the both inside & outside of the stagnation region performed. In current study effect of impingement only on the outside film cooling effectiveness has been studied. At blowing ratio 1.0 & 1.5 slightly higher effectiveness at the stagnation row has been observed as compared to without impingement case. 1.5 R leading edge has been observed to have highest effectiveness in cases with impingement.

5.6 Overall average effectiveness of region of interest

Highest overall average has been observed in 1.5 R leading edge with Impingement ON, Gill Hole ON at DR 2.0. Figure 12 shows the comparison of overall averages with varying density & blowing ratios. However overall average might not be true representative of the film cooling effectiveness in case of leading edge since as observed in low blowing ratio cases with Gill Hole ON, coolant flow to the stagnation might be completely shutoff but the overall average can still remain comparable. Therefore in case of leading edge both overall average & localized averaged effectiveness must be brought in to consideration. Figure 13 compares overall averaged effectiveness.

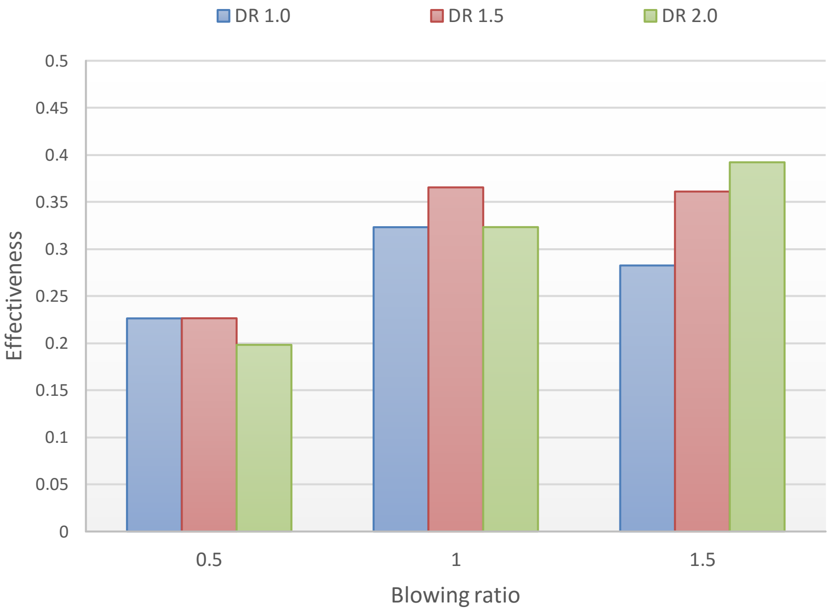

Figure 13: Overall averaged effectiveness R 1.5 Imp ON GH ON

6 CONCLUSION

Comprehensive experimental investigation of film cooling effectiveness of three different leading edges of radius 1 R, 1.5 R & 2 R has been carried out at various coolant flow conditions such as with/without gill holes & with/without internal impingement. A total of 108 cases have been tested. Following s the summary of important conclusions,

6.1 Effect of blowing ratio

- Effectiveness increases with increasing blowing ratio
- Blowing ratio M 0.5 can seriously endanger blade health since in some cases complete shutoff of coolant occurs at stagnation region.

6.2 Effect of density ratio

- Increasing density ratio increases effectiveness at blowing ratio M 1.0 & M 1.5, however at M 0.5 the effect is inverted.

6.3 Effect of leading edge profile shape

- Effectiveness decreases with Increasing leading edge profile radius.
- 1.5 R leading edge is reported to have the highest overall effectiveness.

6.4 Effect of gill holes

- Complete shutoff of coolant to stagnation region can occur at M 0.5, since more coolant is taken by gill holes owing to lower outside pressure.

6.5 Effect of internal impingement

- Slightly higher effectiveness observed at stagnation region at M 1.0 & M 1.5 with impingement.

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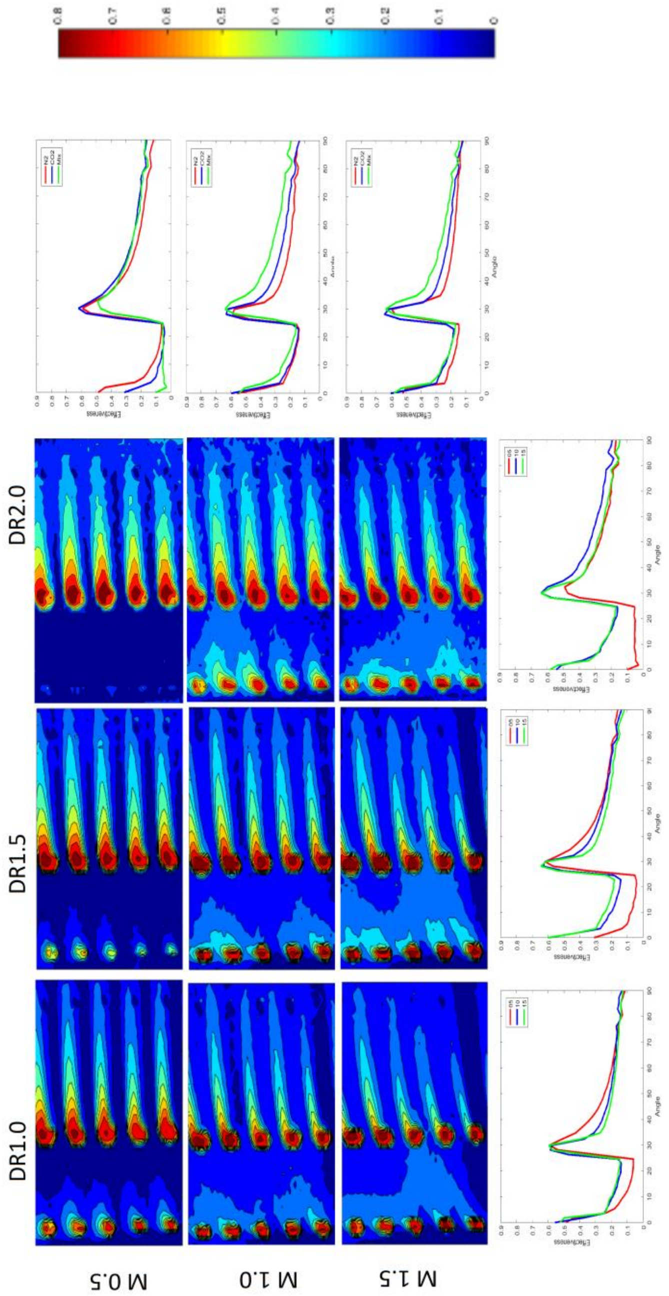
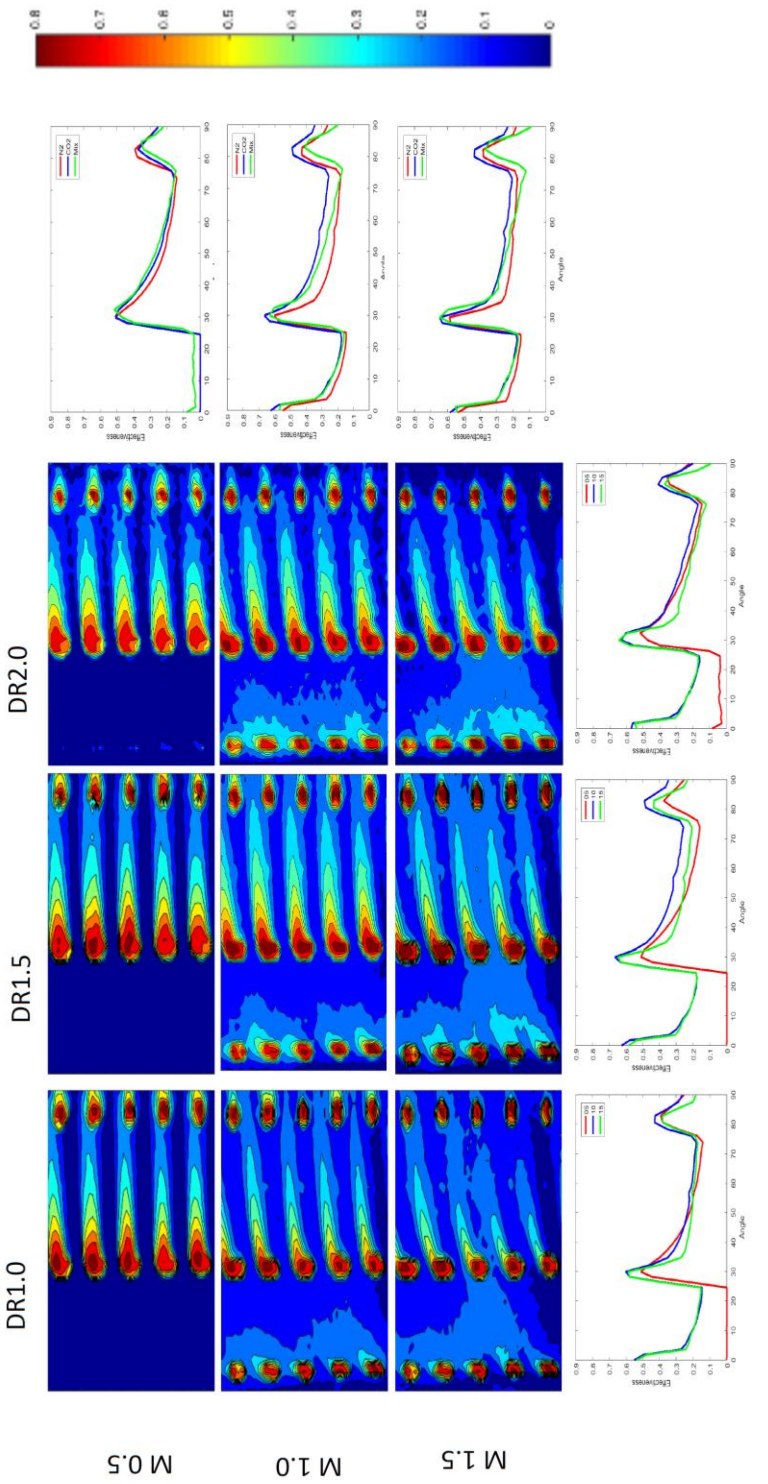
APPENDICES

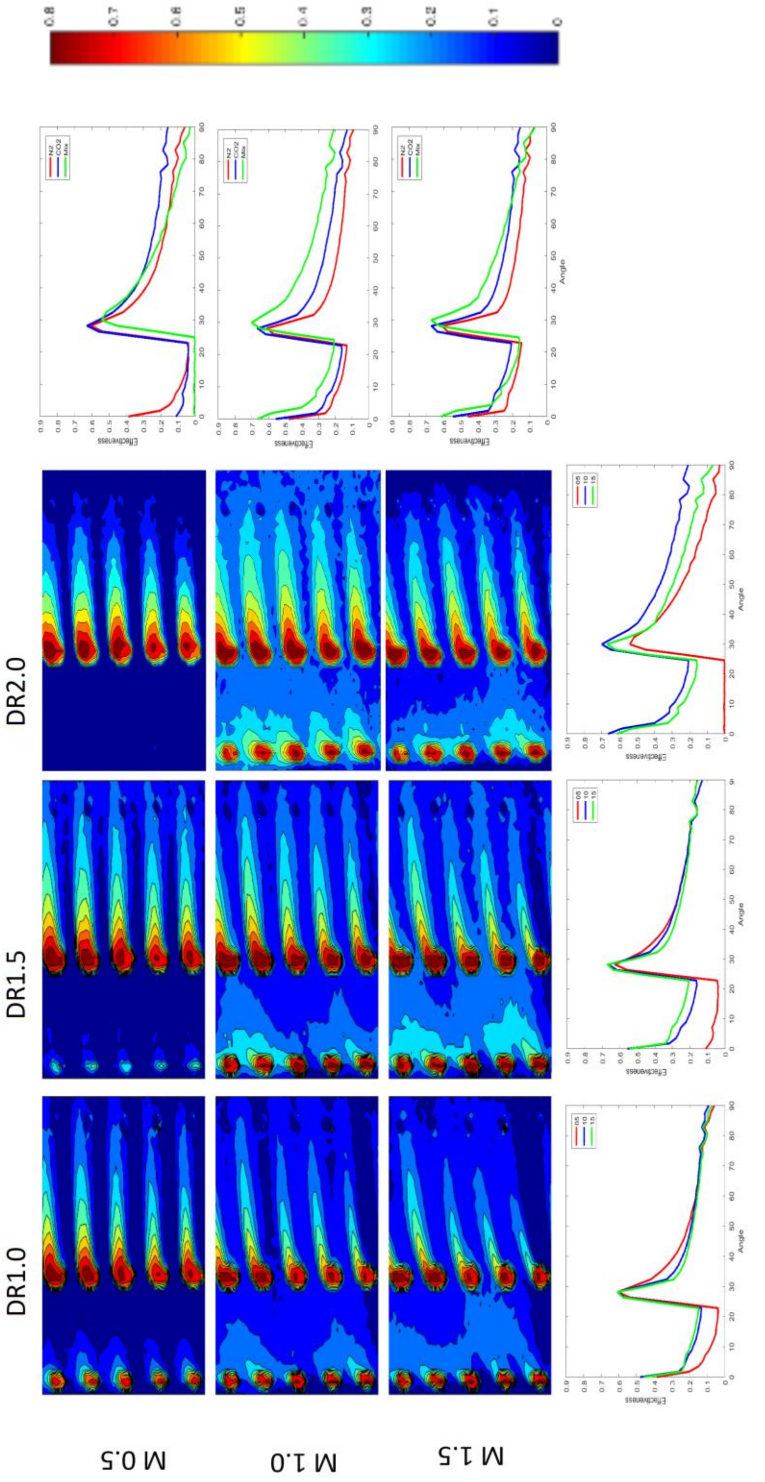
Appendix A – 1 R leading edge



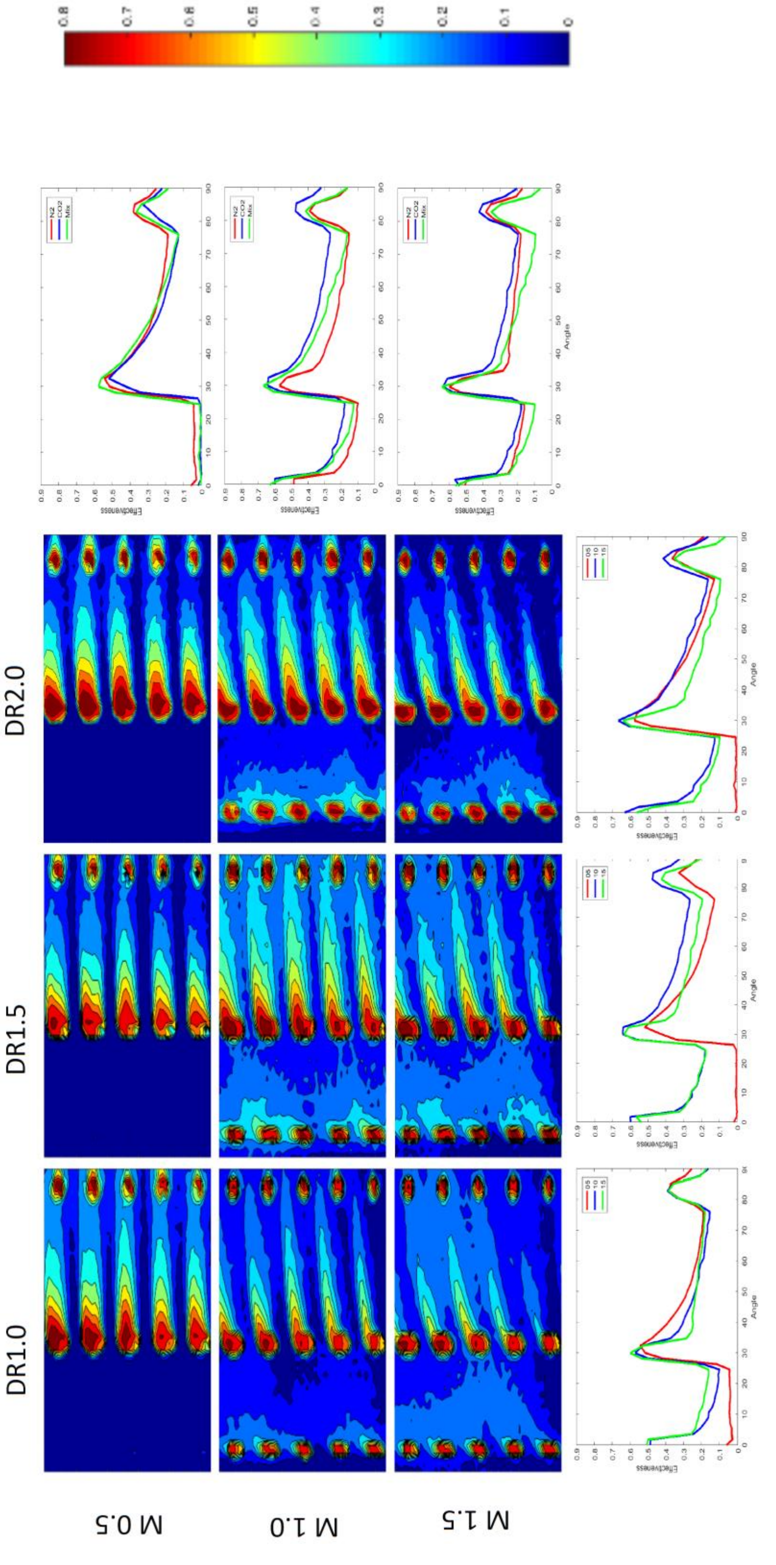
Appendix A 1: Imp OFF GH OFF – 1 R Cylindrical Holes



Appendix A 2: Imp OFF GH ON – 1 R Cylindrical Holes

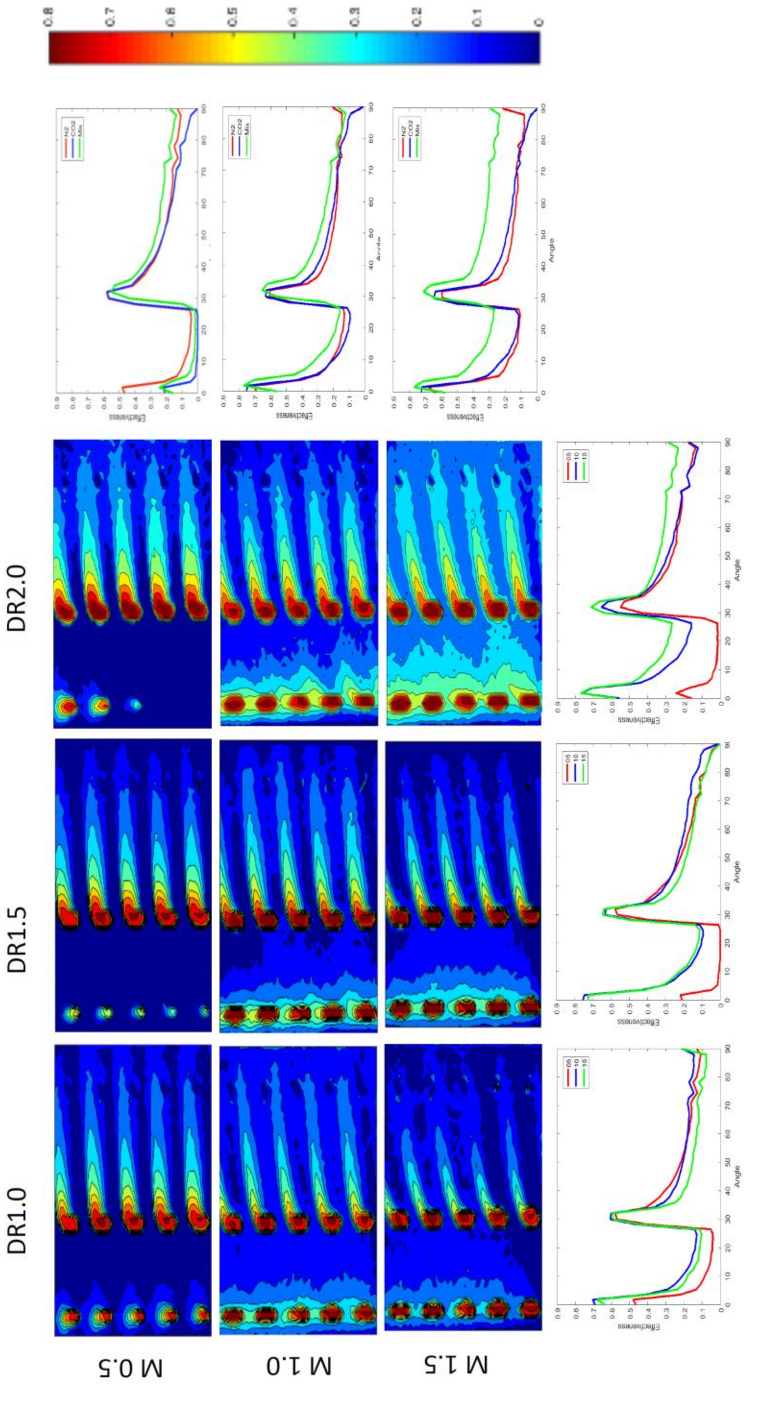


Appendix A 3: Imp ON GH OFF – 1 R Cylindrical Holes

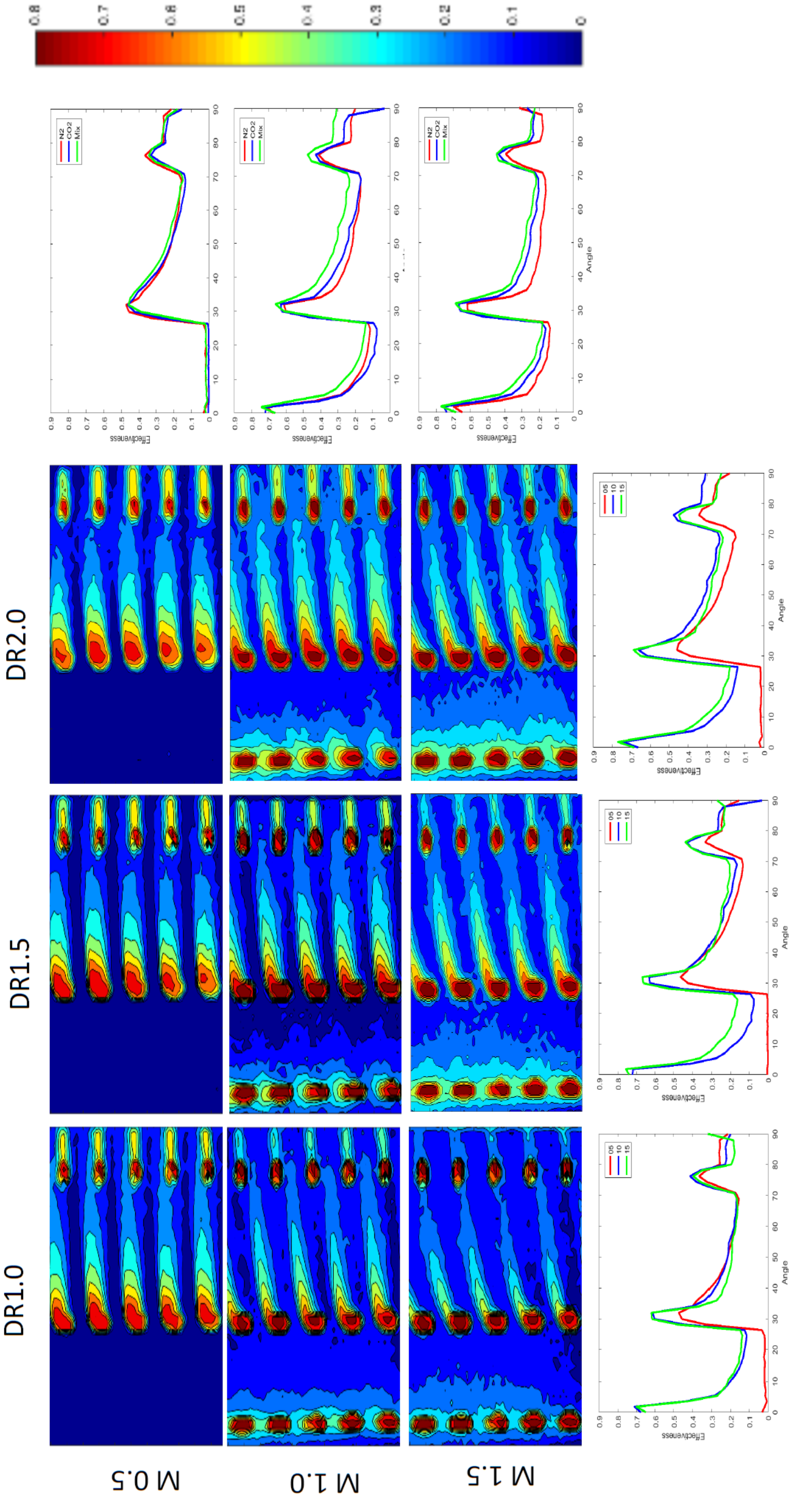


Appendix A 4: Imp ON GH ON – 1 R Cylindrical Holes

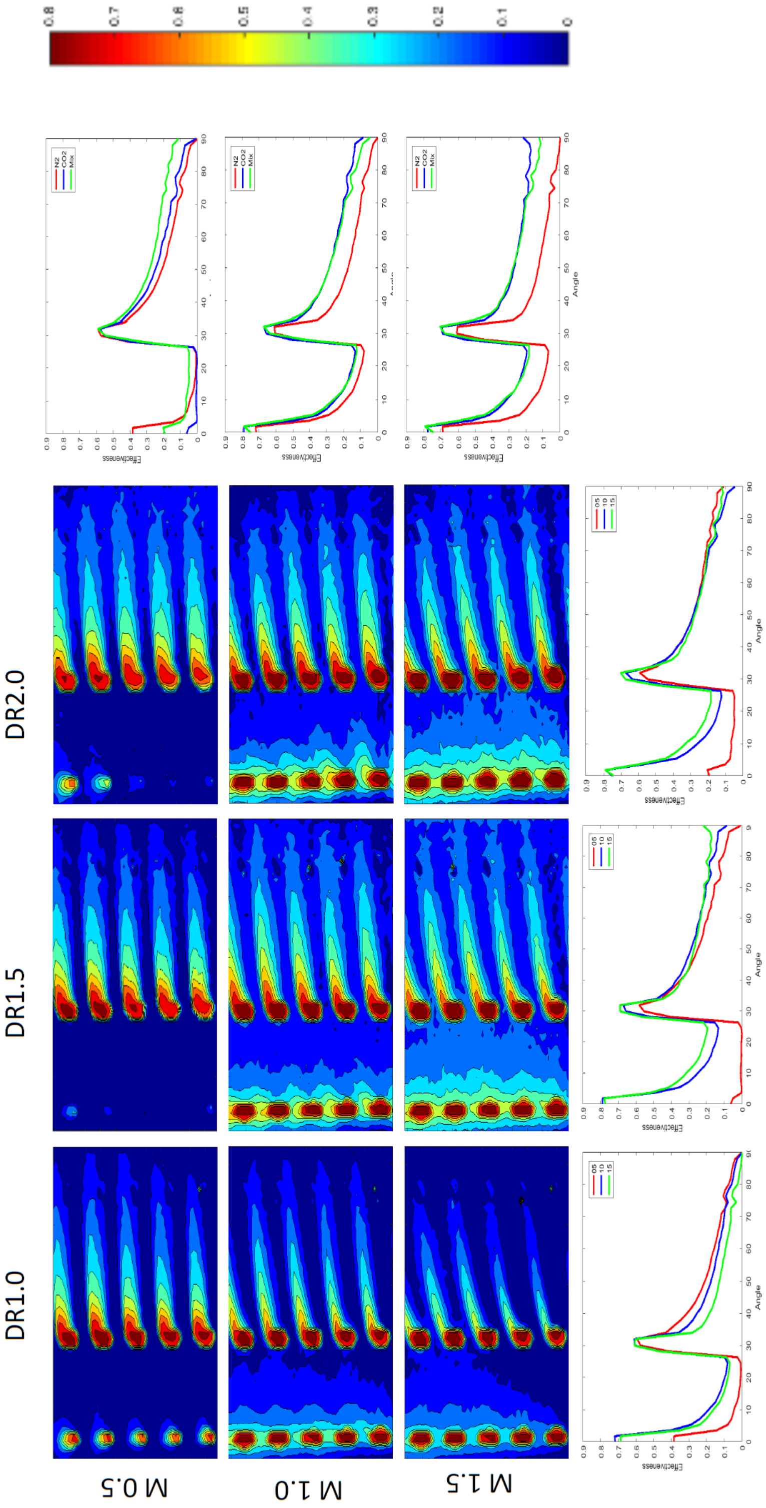
Appendix B – 1.5 R leading edge



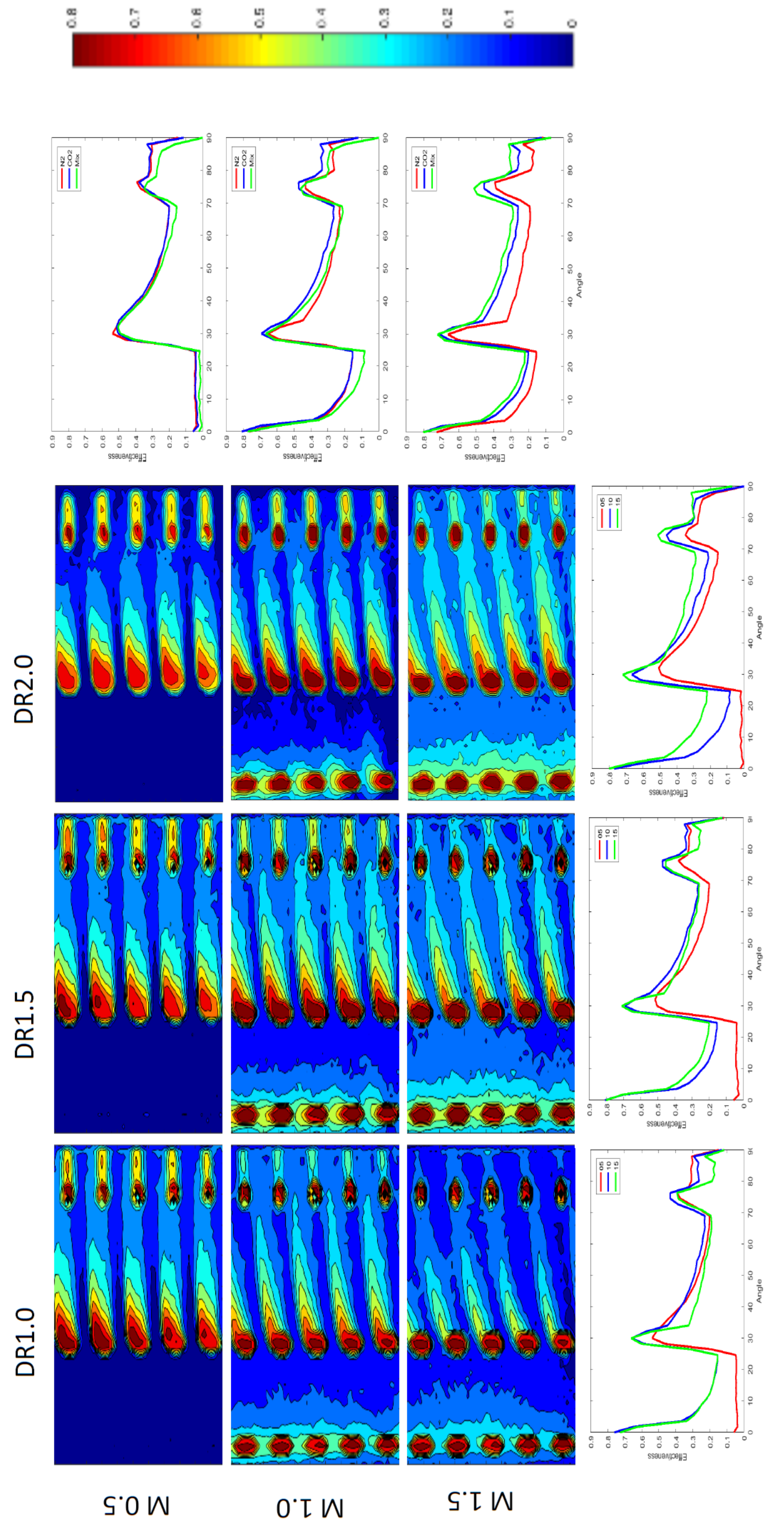
Appendix B 1: Imp OFF GH OFF – 1.5 R Cylindrical Holes



Appendix B 2: Imp OFF GH ON – 1.5 R Cylindrical Holes

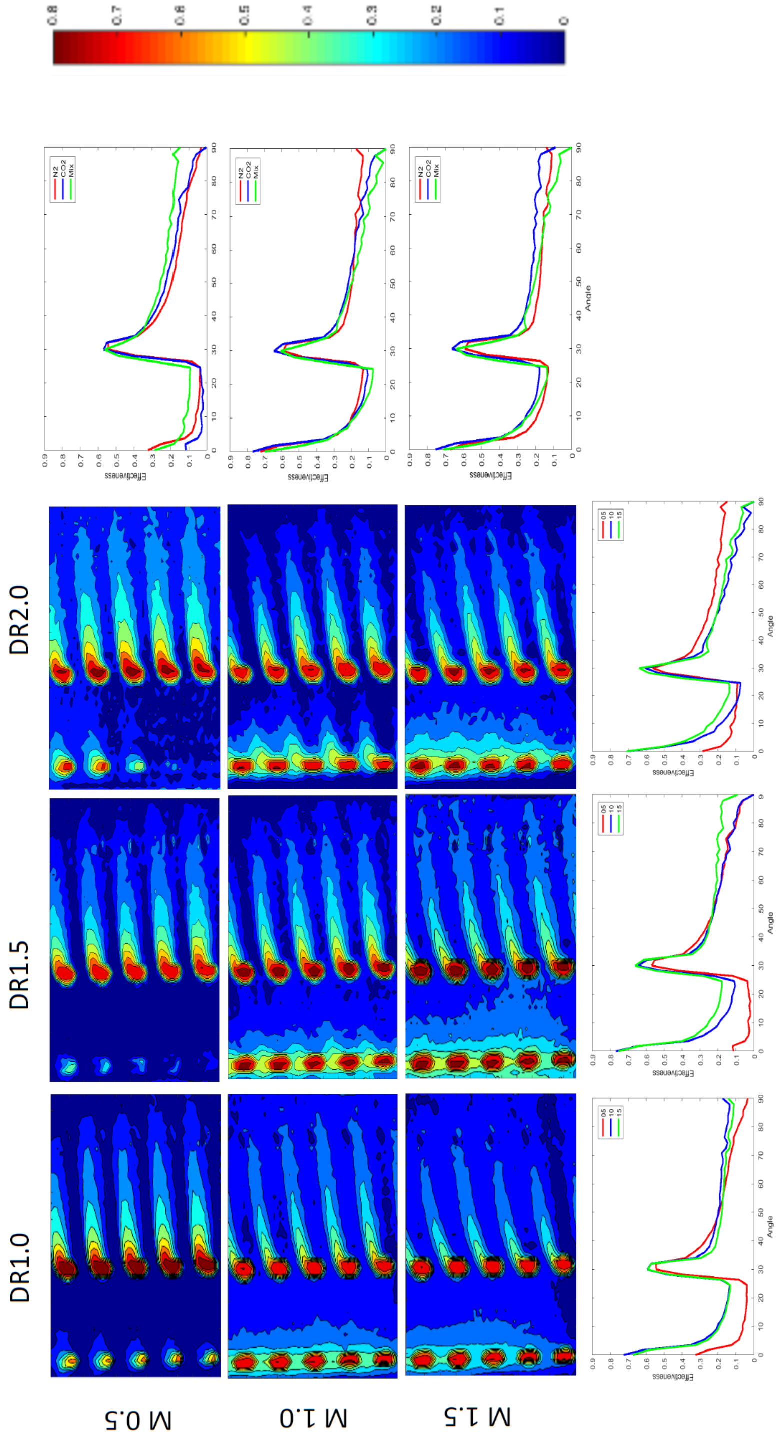


Appendix B 3: Imp ON GH OFF – 1.5 R Cylindrical Holes

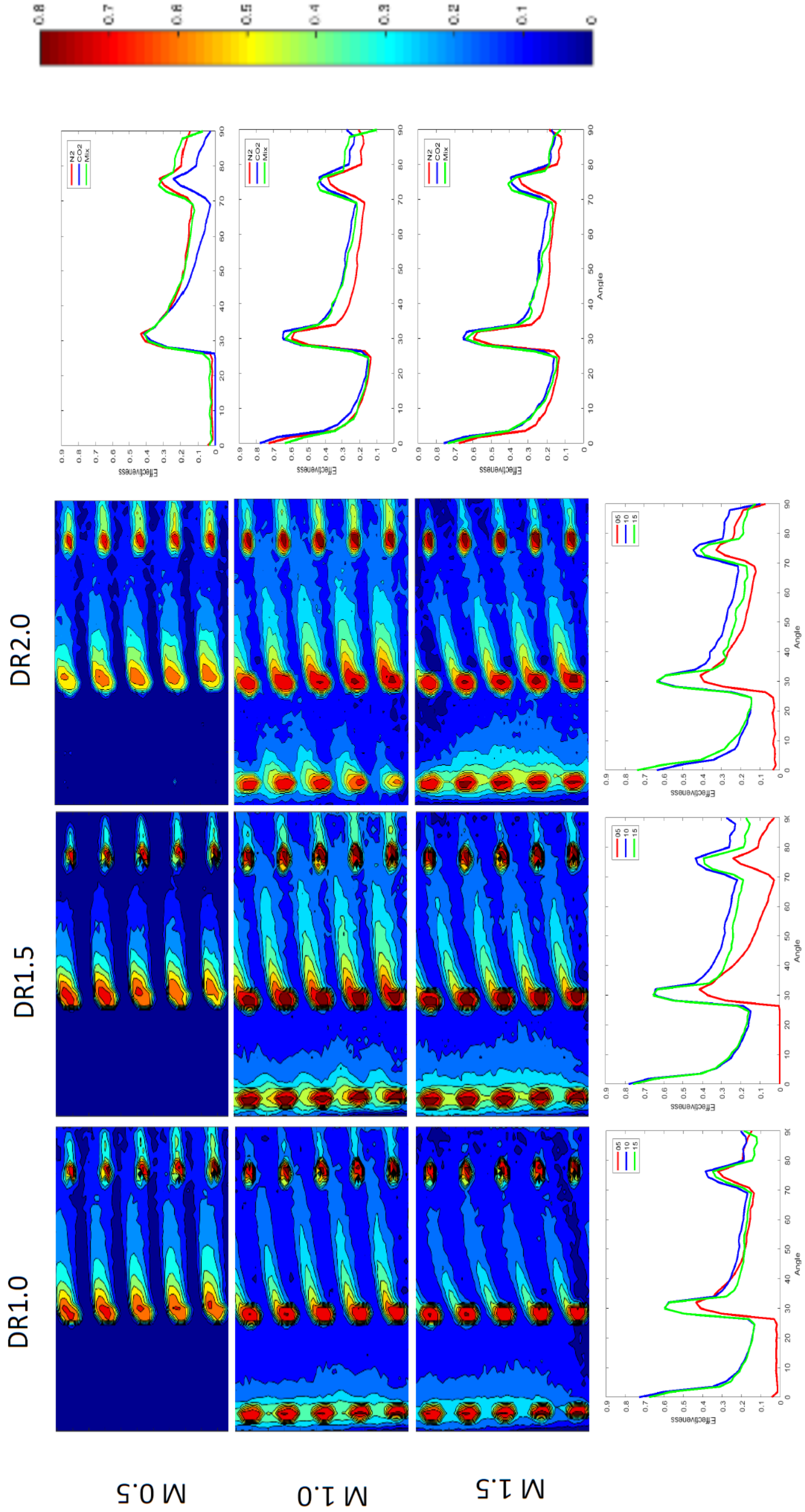


Appendix B 4: Imp ON GH ON – 1.5 R Cylindrical Holes

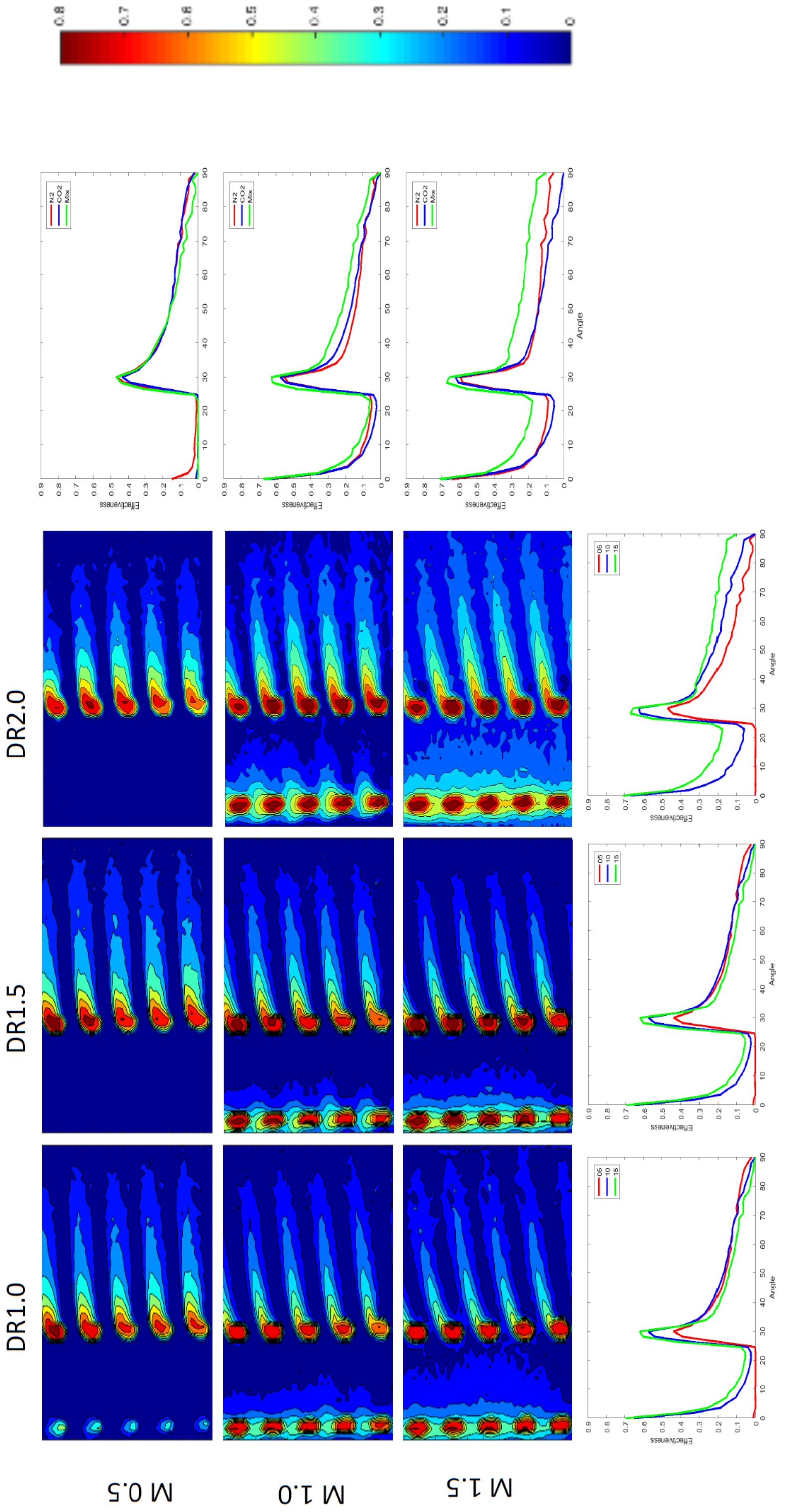
Appendix C – 2 R leading edge



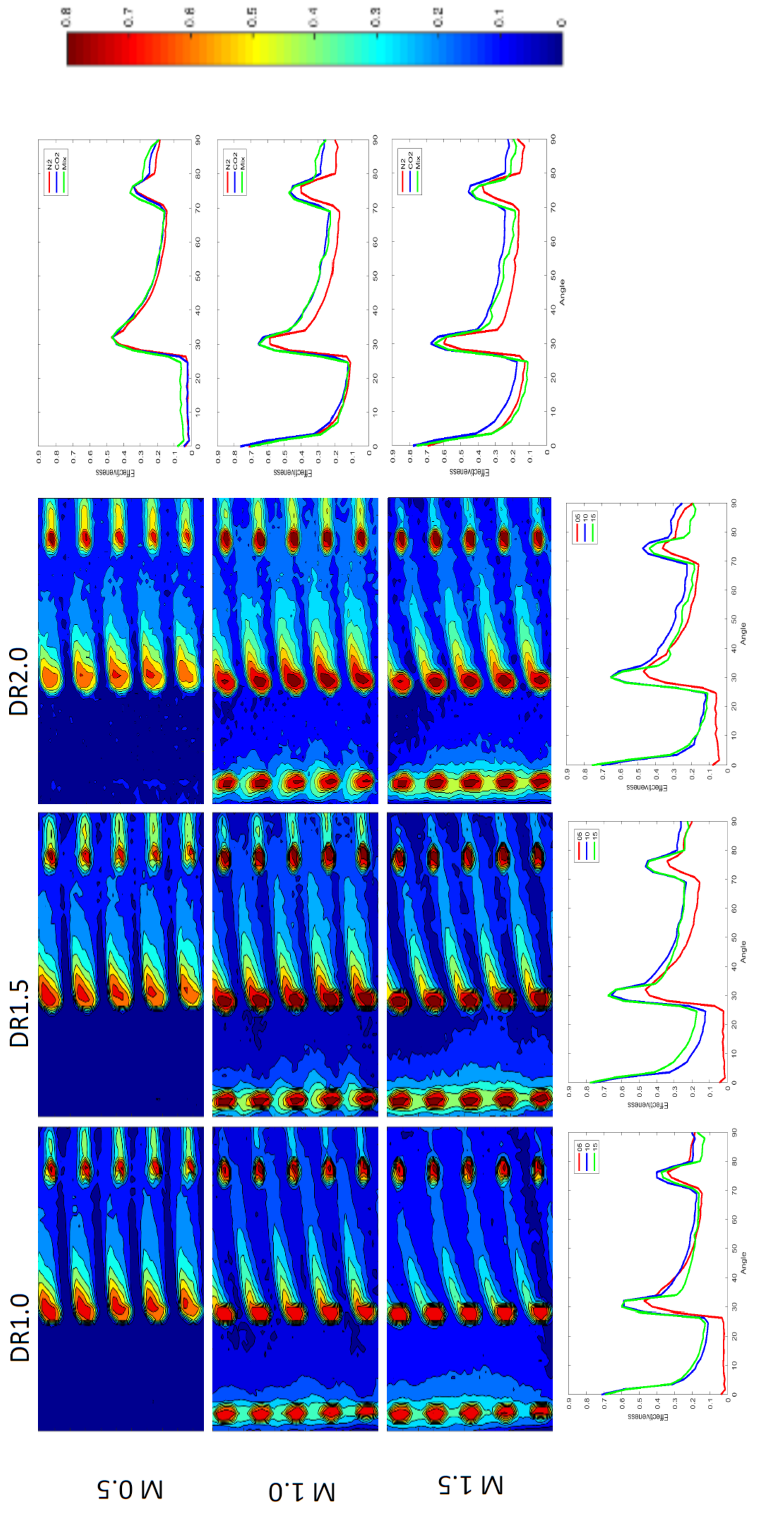
Appendix C 1: Imp OFF GH OFF – 2 R Cylindrical Holes



Appendix C 2: Imp OFF GH ON – 2 R Cylindrical Holes

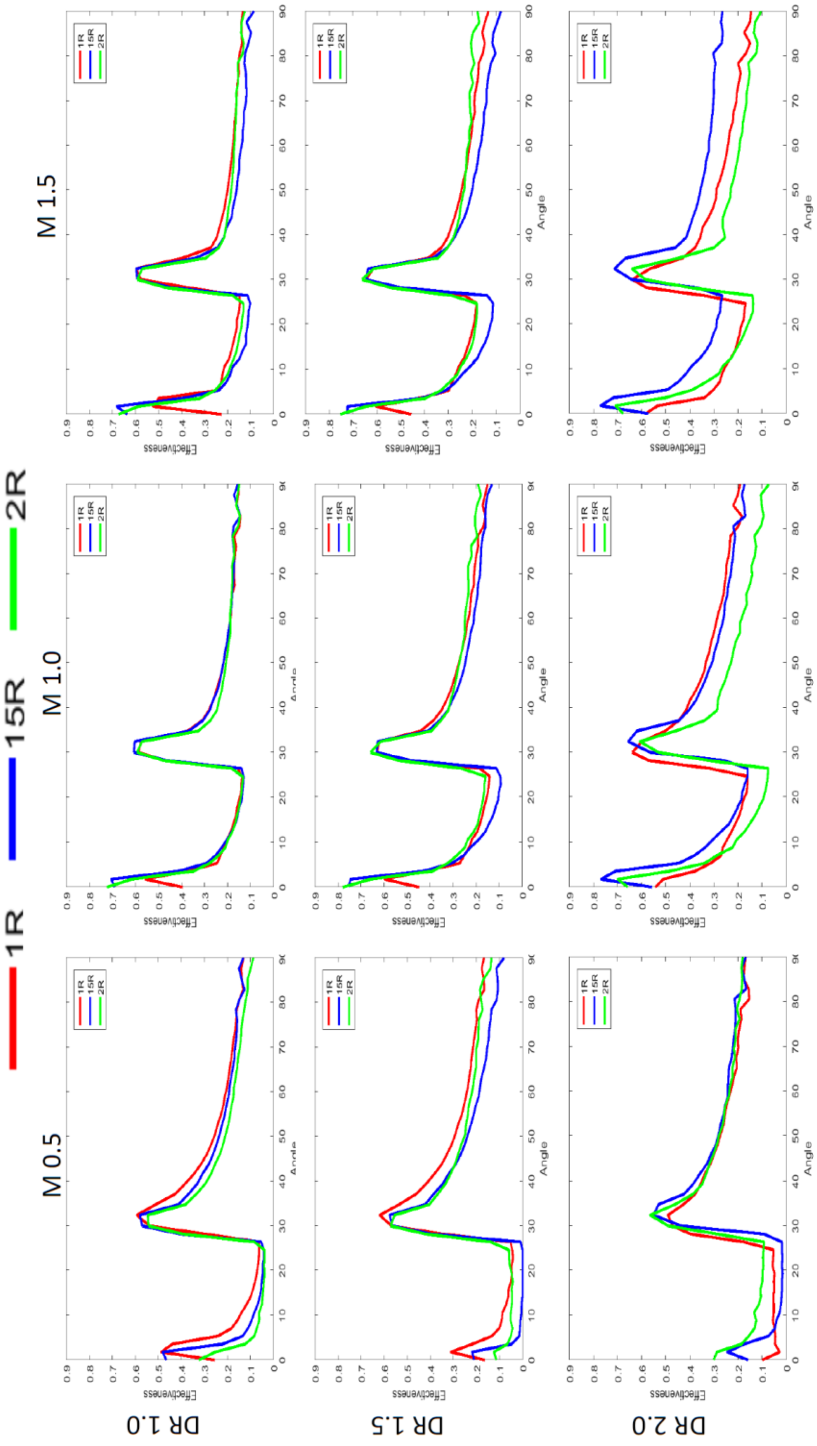


Appendix C 3: Imp ON GH OFF – 2 R Cylindrical Holes

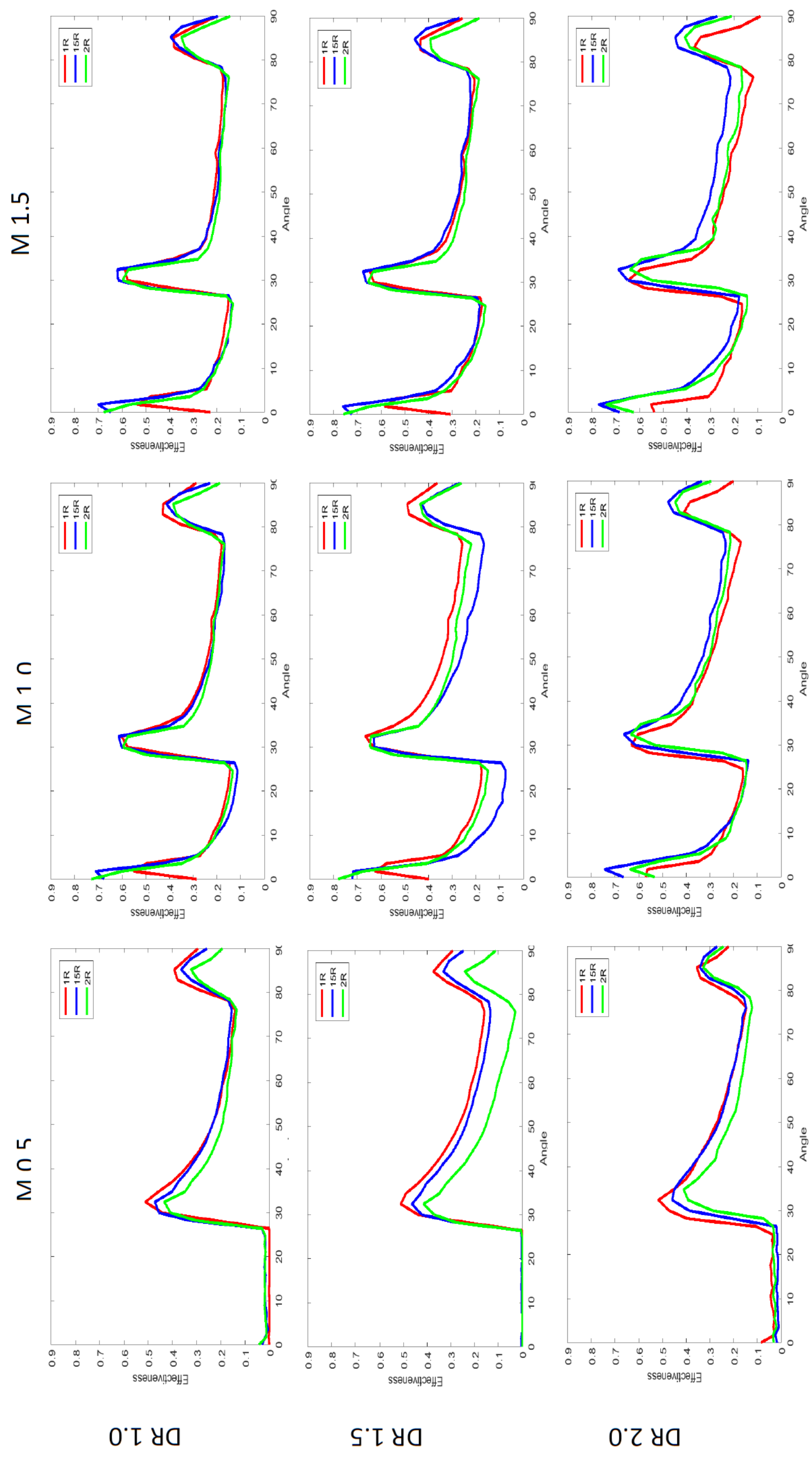


Appendix C 4: Imp ON GH ON – 2 R Cylindrical Holes

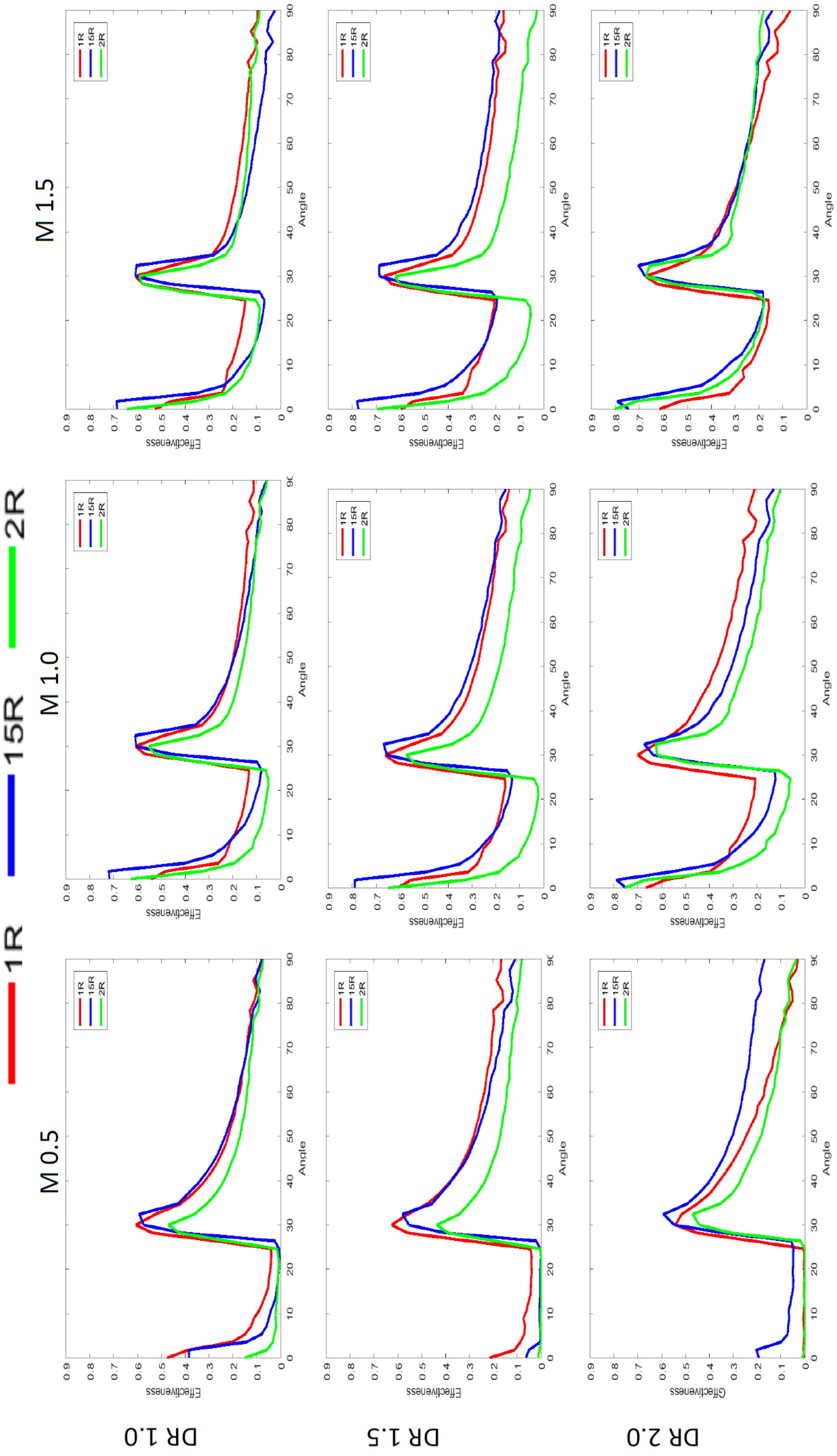
Appendix D – Profile effect



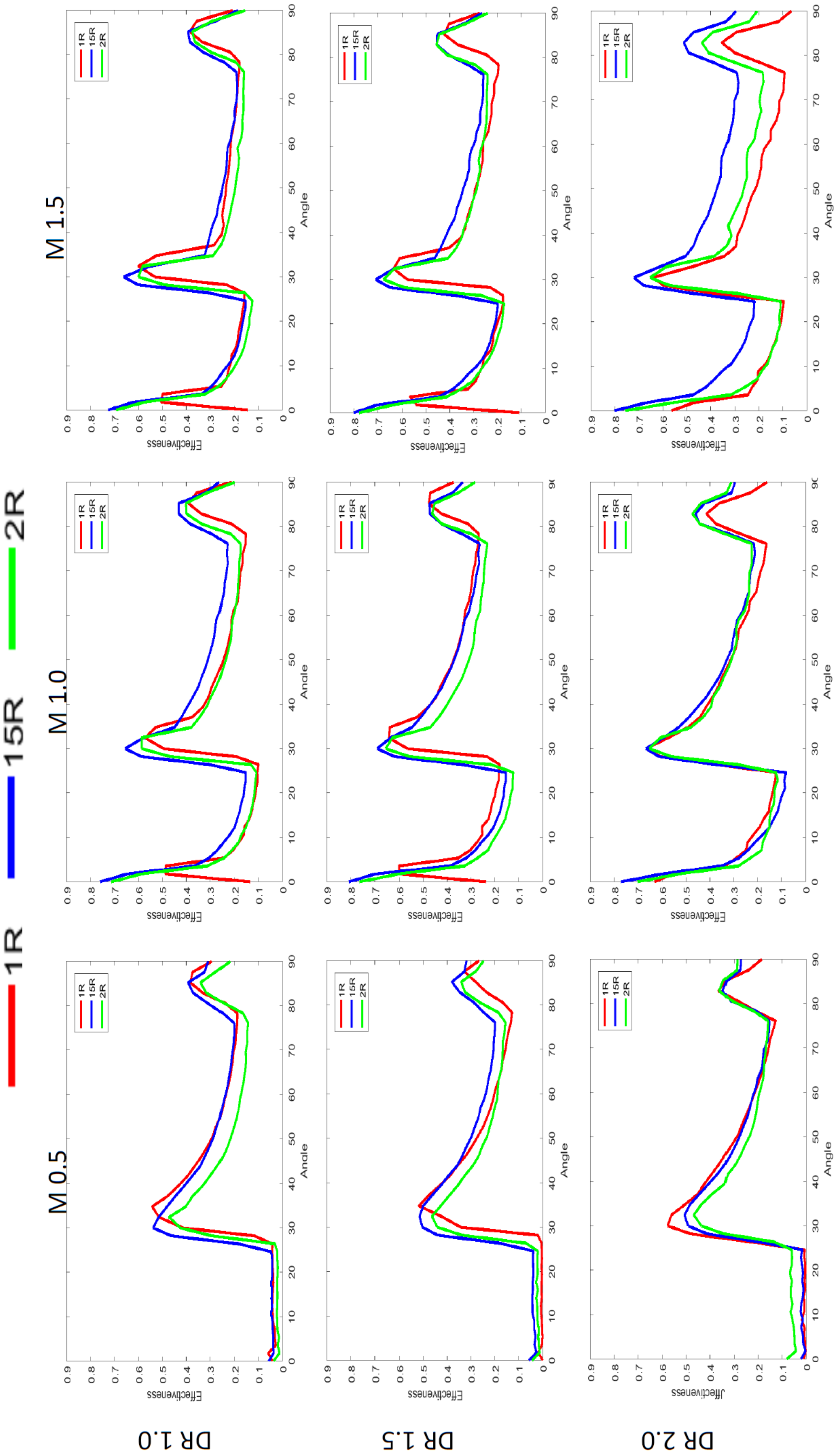
Appendix D 1: Imp OFF GH OFF



Appendix D 2: Imp OFF GH ON

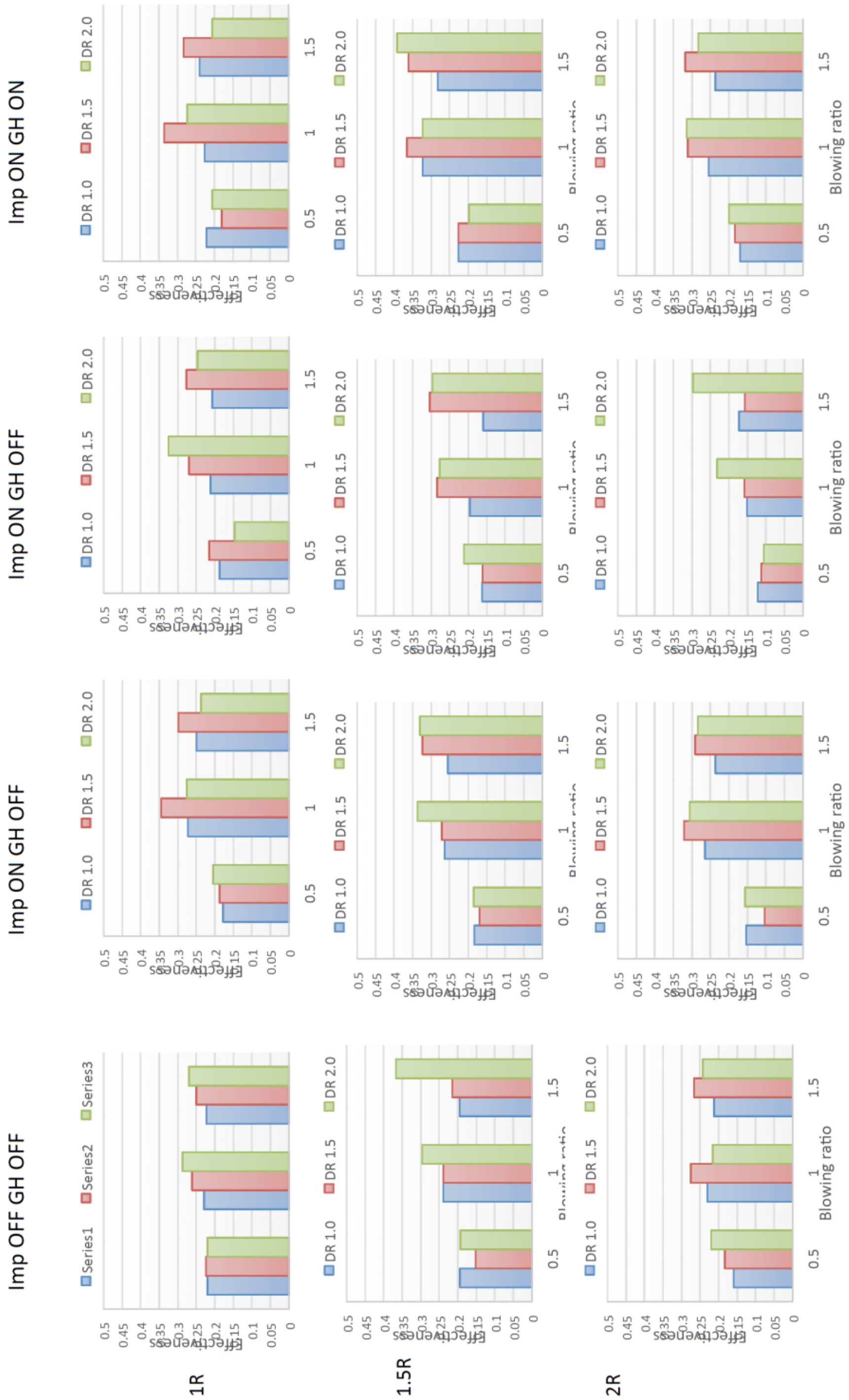


Appendix D 3: Imp ON GH OFF



Appendix D 4: Imp ON GH ON

Appendix E – Overall surface average effectiveness



Appendix E 1: Overall surface average effectiveness