

# Effect of Impeller Blade Slot on Centrifugal Pump Performance

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## Abstract

The effect of impeller backward blades with slot on the centrifugal pump performance has been investigated numerically. Impeller blades have been modified with different geometrical parameters of slot such as: slot radial position (Rs), slot height (hs) and slot inclination angle (?s). 3-D numerical simulation has been carried out using commercial software, ANSYS® CFX, to study the effect on the pump performance at different flow rates. The numerical simulation has been compared with previously published experimental results to verify the numerical solution. In addition, the results have been compared with the impeller without slots for the same operating conditions. It has been shown that the slot parameters have a significant effect on the centrifugal impeller performance.

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**Index terms**— computational fluid dynamics (CFD), blade slot, centrifugal pump performance.

## 1 I. Introduction

Centrifugal pumps are probably among the most often used machinery in industrial facilities as well as in common practice. After being invented, they passed long evolutionary way until they became accessible for various applications. A few centuries ago, Euler described their physical principle through a wellknown equation named after him "Euler's equation for turbomachinery".

Since then, many studies have been conducted to improve the centrifugal pump performance. These studies used a lot of methods and ideas seeking a better centrifugal pump performance through attempts to increase the pump total efficiency and slip factor.

One of these methods that took a lot of interest was to improve the pump performance by impeller trimming [1][2][3][4]. These studies found that as the diameter is reduced, the head and power curves decrease continuously. The efficiency, however, will increase at first and then drop for a certain value of diameter. The main reason for this might be attributed to the growth of the gap between the impeller and stator as the impeller diameter is reduced.

Another attempt to improve the centrifugal pump performance lies in adding splitter blades between the main blades [5][6][7]. Unfortunately, such solution was found to render negative and positive effects on the pump behavior. It increases the head as compared to the original impeller. This was explained by the fact that increasing the impeller slip factor in effect of the splitter would help better conduct energy to the flow. However, a drop in total efficiency has been noticed in some cases due to the increase of the hydraulic friction between the pumping fluid and the splitter blades.

The pump geometrical parameters remain the greatest interest of all researchers looking for improving the centrifugal pump performance. Some authors made optimization on the blade exit angle and they found that with increasing the blade exit angle the head increases but the efficiency decreases [8][9][10][11][12]. Some other authors conducted optimization on the number of blades [13][14][15]. They concluded that when increasing the number of blades, both head and efficiency increase until a certain number of blades at which the efficiency decreases. Other authors considered the blade outlet width in their optimization research [16,17]. It was found that at the design flow rate, the head increases gradually with the progressive increments of blade outlet width. In addition, the high efficiency area in the large flow rate region gets bigger and the area in low flow rate region changes a little with the increase of blade outlet width.

## 5 EFFECT OF IMPELLER BLADE SLOT ON CENTRIFUGAL PUMP PERFORMANCE

Some authors tried to improve the pump performance by making a slot in the impeller blade. The first one who start adopting this technique was E.A. Ahmed [18,19]. Then, M. Saffaa and his group [20][21][22] developed this work using their own 2-D numerical code to solve a laminar flow inside the pump impeller. In an attempt to examine the effect on the pump performance, Hongxun [23] used a similar technique and made a comparison between the draughting technique and the splitter blades.

In the present work, a parametric study is attempted, based on the blade slot technique to investigate the effect of three slot geometrical parameters, namely slot radial position ( $R_s$ ), slot height ( $h_s$ ) and slot inclination angle ( $\theta_s$ ) on the impeller performance. The study implements a 3-D numerical simulation of turbulent flow inside the centrifugal impeller.

## II. Computational Model a) Geometrical Models

The centrifugal pump impeller used by [20,24], shown in Figure (1), is chosen as a geometrical model to apply numerical computation. The main metrics of pump design and performance are listed in Table (1).

### Table 1: Pump dimensions and operating conditions

The flow patterns and the hydraulic performance of the isolated impeller (without volute) must differ from that of the impeller with volute [25]. This difference is due to impeller-volute interactions. In this work, only an isolated impeller has been considered. This is justified by the need to simplify the present study that is considered as a preliminary investigation. Numerical simulation is carried out using ANSYS® CFX to solve the governing equations. Since the pumped fluid is incompressible and the flow is in a steady state, the continuity equation has the following form [26]:

$$(1)$$

In addition, the equation of conservation of momentum together with the definition of the source term, and the shear stress is expressed as Eq. (??) (2) where the source term (including the centrifugal and Coriolis force terms) is written as Eq. (??) and the average shear stress is obtained from Eq. (??):

$$(3) (4)$$

## c) Computational Domain

The computational domain consists of three zones: inlet, impeller and outlet as shown in Figure (3).

They are defined by means of the multi-reference frame technique. The impeller is situated in the rotating reference frame, the inlet and outlet zones are in the fixed reference frame, and they are related to each other through the "frozen rotor" interface. The frozen rotor method [26] employs a quasi-steady algorithm, where the rotor and stator are modeled at a fixed (frozen) position relative to each other. Rotational terms are included in the moving frames, while the transient effects are neglected. This provides an efficient method for the calculation of interactions between impellers and outlet zone, and is a practical option for compact machines with small distances between rotor and stator. In this way, the solution provides a snapshot of the flow regime. When the Navier-Stokes equations of motion are solved in a rotating reference frame, the fluid accelerations due to rotation appear as an additional terms in the momentum equations, Eq. (??). The meshes of three computational domainsthe inlet section, the impeller, and the outlet sectionare generated separately after performing mesh sensitivity analysis as shown in Figure (4). In this analysis, localized refinements of mesh are employed at regions close to the blade slot, the impeller blade and the blade leading and trailing edges in order to accurately capture the dominant flow field structure.

## 5 Effect of Impeller Blade Slot on Centrifugal Pump Performance

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot (\mu \nabla \mathbf{u}) + \rho \mathbf{g} + \mathbf{S}$$

The motive of this localized mesh refinement is to encounter considerable variations of flow field properties such as pressure and velocity at those regions. The boundary conditions are set as mass flow at inlet and the static pressure at outlet. A rotational periodicity is adopted at the other outer boundaries of the domain. A no-slip condition is imposed at the wall boundary defined at the blade. The impeller zone is modeled in the rotating frame, and the outlet and the inlet zones are modeled in the fixed reference frame. The comparison between the experimentally measured impeller performance with and without blade slot in reference [20] is used to validate the present study. The pump with slot has the following parameters: slot radial position  $R_s = 35$  mm, slot height  $h_s = 8$  mm and the inclination angle  $\theta_s = 0^\circ$  at rotational speed  $n = 2000$  rpm.

(5) (6) Figure (8) and Figure (9) show the variation of the impeller head and hydraulic efficiency with flow rate, respectively, for both impellers with and without slot. Experimental measurement show that the slot with the parameters of reference [20] reduces the impeller head. The slot shows a minor impact on the efficiency however, adding the slot increases the efficiency below the operating point and reduces the efficiency beyond the operating point. These effects of adding slot could be explained by the considerable reduction in the effective blade length and augmentation of flow rate through the slot, which in this case represents about 17% of the design flow rate.

103 Despite the apparent discrepancy between experimental and numerical results, the numerical simulations  
104 predict the same trend of head and efficiency. They also predict the same effect of slot on pump head at all flow  
105 rates and efficiency at high flow rate only. This discrepancy could be attributed to the omission of the volute  
106 and leakage effects in the numerical simulation.

## 107 6 g) Convergence Criteria of the Numerical Simulations

108  
109 The numerical solution has convergence precision of residuals up to  $10^{-6}$ . Figure (7) shows the history of  
110 convergence.

111 Here, the pump head and hydraulic efficiency are calculated according to reference [28] by using Eq. (??) and  
112 Eq. (??). The velocity vectors at two different flow rates are investigated;  $Q = 1$  liter/s, at part-load condition  
113 and  $Q = 3.5$  L/s at the best efficiency point. In Figure (10), the velocity vectors for part load condition indicate  
114 two circulations: the first one is created on the pressure side near the impeller outlet with a small size and high  
115 velocity. The second one is created on the suction side with large size and small velocity. The flow enters the  
116 impeller at an angle of attack causing the suction side circulation. In the presence of the slot, the fluid flowing  
117 throughout the slot reduces the size of the suction side circulation. Figure (11) indicates the absence of the  
118 two circulations. When increasing velocity the pressure side circulation dies out, and when the angle of attack  
119 approaching zero the suction side circulation is disappears.

120 The static pressure contours are also investigated at the flow rate  $Q = 3.5$  liter/s. Figure (12) Shows the  
121 contours of the static pressure of the impeller with and without blade slot.

122 In conclusion, the head decreases at large values of the slot height  $h_s$ . Therefore, in the present study,  
123 attention will be directed to a smaller slot height. A single arc blade design is assumed, and the pump speed is  
124 chosen  $n = 1500$  rpm with impeller outer diameter  $D_2 = 130$  mm and impeller inner diameter  $D_1 = 50$  mm. The  
125 other dimensions are chosen according to Table (1). Fifteen cases have been studied to cover the slot parameters  
126 that affect the impeller performance, Table (2). When making a slot in the impeller blade the fluid goes through  
127 this slot from the pressure side to the suction side with certain flow rate. The convergence of this mass flow rate  
128 is shown in Figure (13).

## 129 7 Table 2: Different cases of slot parameters a) Effect of Slot Radial Position

130  
131 The effect of the variation of the slot radial position  $R_s$  on the impeller performance is studied by changing its  
132 value and keeping the values of the other parameters constant; Cases (1)(2)(3)(4)(5) in Table (2). Figure (14)  
133 shows the head versus the slot radial position. It is found that the head decreases with increasing  $R_s$  in other  
134 word; a slot located closer to the blade root is preferred for all value of flow rate inspected. No improvement  
135 in the impeller performance has been detected. In addition, Figure (15) shows that  $R_s$  has a small impact on  
136 the impeller hydraulic efficiency. The effect of the slot inclination angle on the impeller head is addressed in the  
137 cases (6)(7)(8)(9)(10). From the blade geometry there is a constrain on the slot inclination angle and it should  
138 be chosen according to Eq. (??) (7) where  $\theta =$  blade angle at slot radial position  $R_s$ ,

## 139 8 c) Effect of the Slot Height

140 Finally, the effect of the slot height on the impeller head is examined, cases (11)(12)(13)(14)(15). Figure (18)  
141 shows that with increasing slot height the head increases up to certain value then it decreases. Figure (19) shows  
142 the impeller hydraulic efficiency. It decreases with the increase of slot height. results show that the high negative  
143 inclination angle causes higher heads as shown in Figure (16). This increase in head was due to the rise in slip  
144 factor. The effect of the slot inclination angle on the hydraulic efficiency of the impeller is shown in Figure (17).  
145 Sharp reduction in efficiency is noted at slot inclination  $\theta_s < 110^\circ$  this drop in efficiency is attributed to the  
146 high change in the relative velocity direction. A similar drop in efficiency can be noted in at slot inclination angle  
147  $\theta_s > 0^\circ$ .

148 Global Journal of Researches in Engineering ( ) Volume XVI Issue IV Version I Figure (20) shows the relative  
149 velocity vectors on the mid span at flow rate  $Q = 4$  L/s (case 11) for impeller with and without slots. Formation  
150 of a vortex on the suction side with the same angular direction of the impeller rotation increases the slip factor  
151 and hence increases the head.

152 Figure (21) shows the difference in pressure along the blade pressure and suction sides. Clearly, the pressure  
153 difference above the slot is higher than the pressure difference in case of blade without slot.

154 To illustrate the effect of the blade slot on the performance of the impeller, the pressure contours and the  
155 velocity vector inside the slot are shown in Figure (22) and Figure (23). The pressure contours inside the slot  
156 show that the pressure force in the slot with inclination angle (case 3) has positive direction with yaxis. In  
157 addition, for (case 9) the pressure force has a negative direction with the y-axis. velocity vector in the blade slot  
158 shows that the velocity has a large value at the slot upper half. In case of high inclination angle the velocity has  
159 a reverse flow in the lower slot region. The velocity in the slot has maximum value (about 5.8 m/s). The flow  
160 rate inside the slot is proportional to the slot height, in case of  $h_s = 1$  mm the slot flow rate is about 0.055 liter/s

161 with the total flow rate equal to 4 liter/s as shown in Figure (13), which represents  $\pm 1.4\%$ . In the present work,  
162 a parametric study is done based on the blade slot technique to investigate the effect of some slot geometrical  
163 parameters, namely slot radial position ( $R_s$ ), slot height ( $h_s$ ) and slot inclination angle ( $\theta_s$ ) on the impeller  
164 performance using a 3-D numerical simulation of a turbulent flow inside the centrifugal impeller, the following  
165 are concluded:

### 9 Global

167  $\theta$  With increasing the slot radial position  $R_s$  the impeller head is decreased. The slot radial position has an  
168 effect less than 2.5% on the impeller hydraulic efficiency when the slot height is 1.5 % of the blade length.  $\theta$  The  
169 slot inclination angle has a significant effect on the impeller head and efficiency. The slot with inclination angle  
170  $\theta 130^\circ < \theta_s < 90^\circ$  has a high impeller head with 5  $\pm 10\%$  above the impeller head without slot. The optimum  
171 efficiency can be reached within the range of slot inclination angle  $\theta 110^\circ < \theta_s < 0^\circ$ .  $\theta$  At the part load operating  
172 zone, the impeller head decreases with increasing the slot height, then at the over load zone the impeller head  
173 increase with increasing the slot height up to certain slot height value then the impeller head decrease. The  
174 efficiency is decreased with the increase of slot height.

175 Attempts have been made to explain the physics of impeller with slot design. The present work is currently  
176 extended by incorporating the complete pump geometry to account for the discrepancies between CFD and  
177 experimental finding.

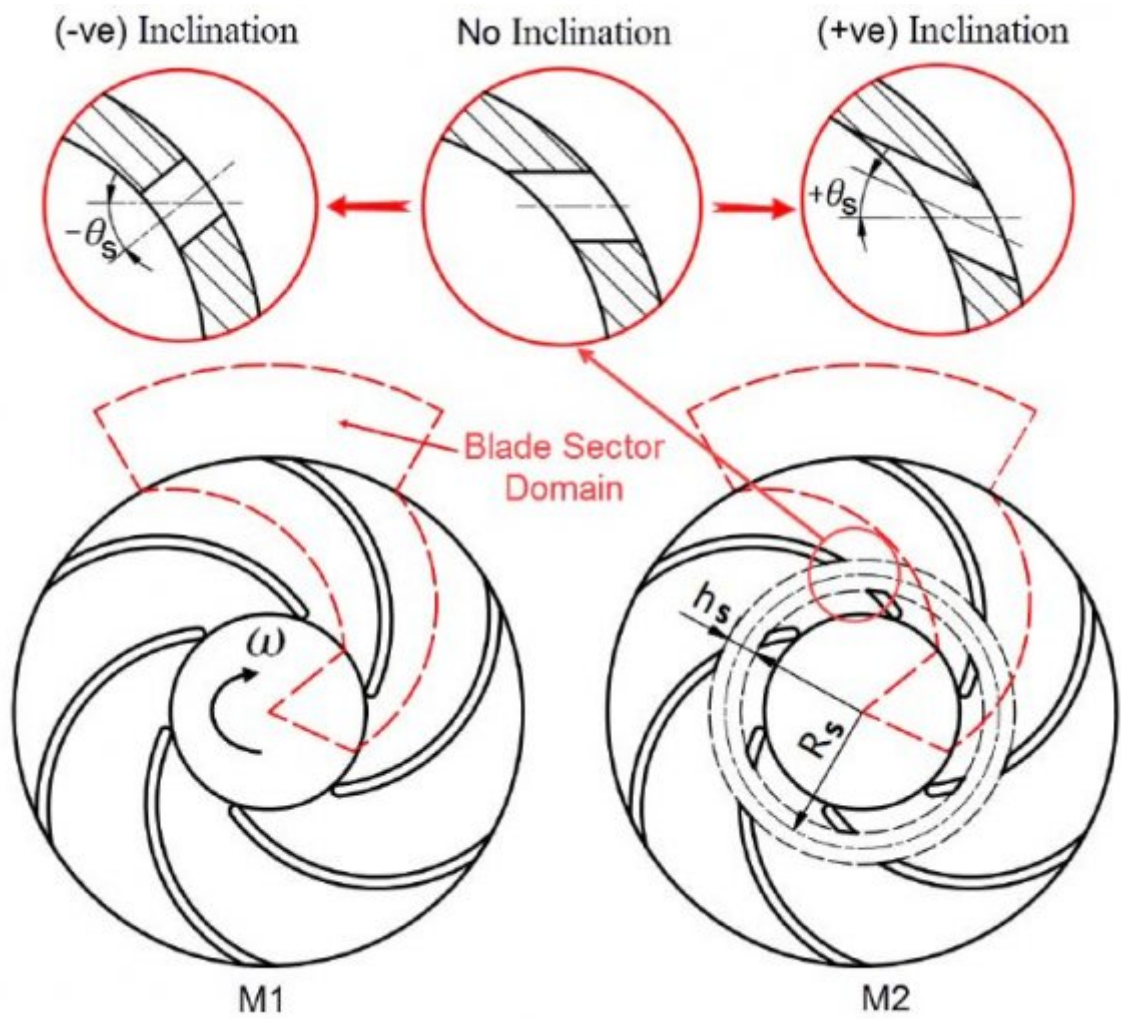
178 The study can be further extended to optimize the slot design parameters at different flow rates for maximum  
pump performance. <sup>1</sup>



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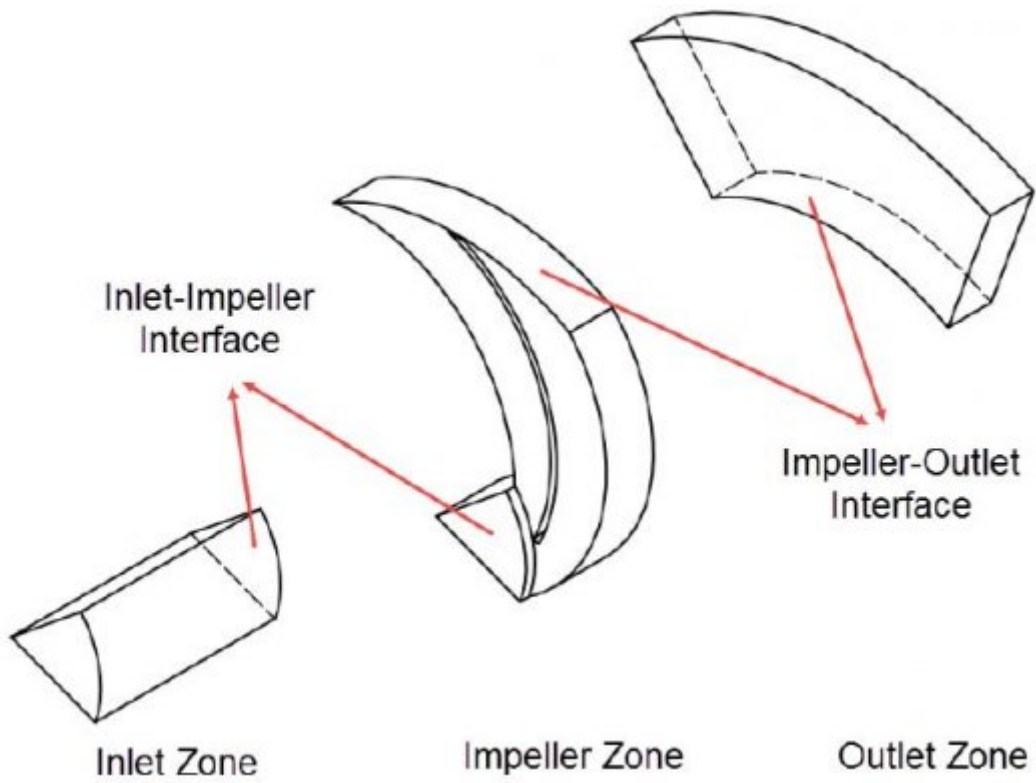
Figure 1: Figure 1 :

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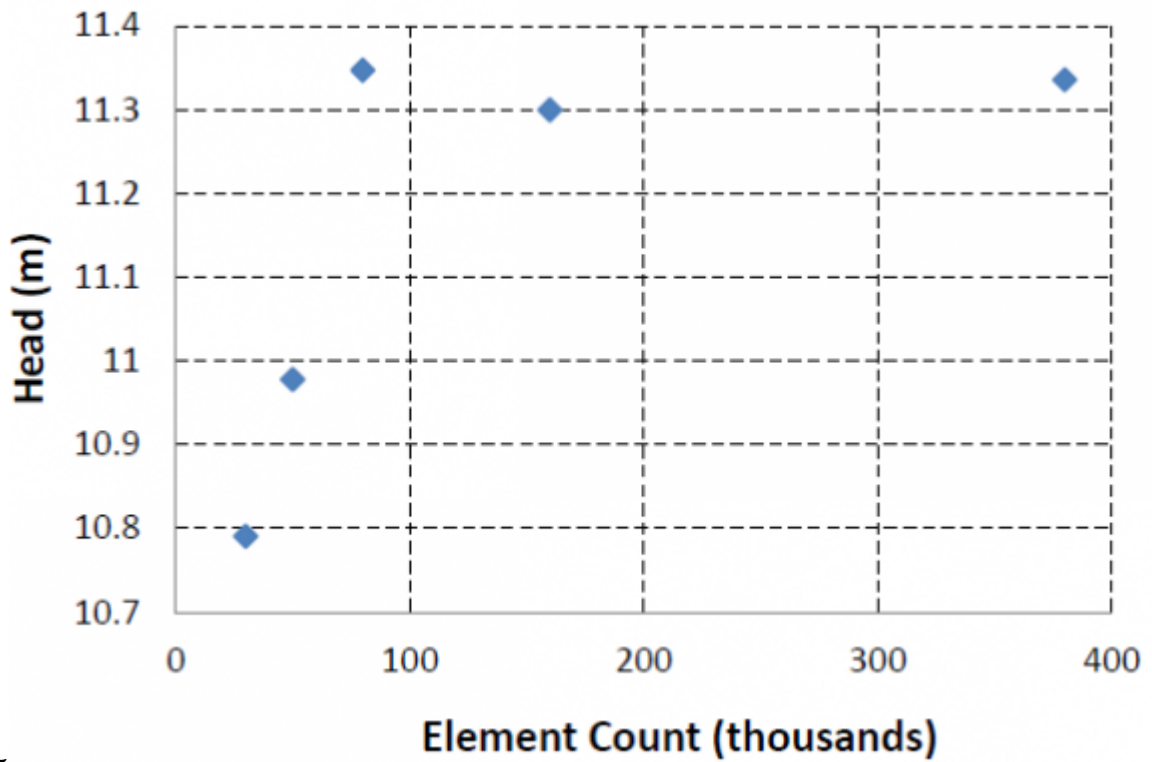
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Figure 2: Figure 2 :



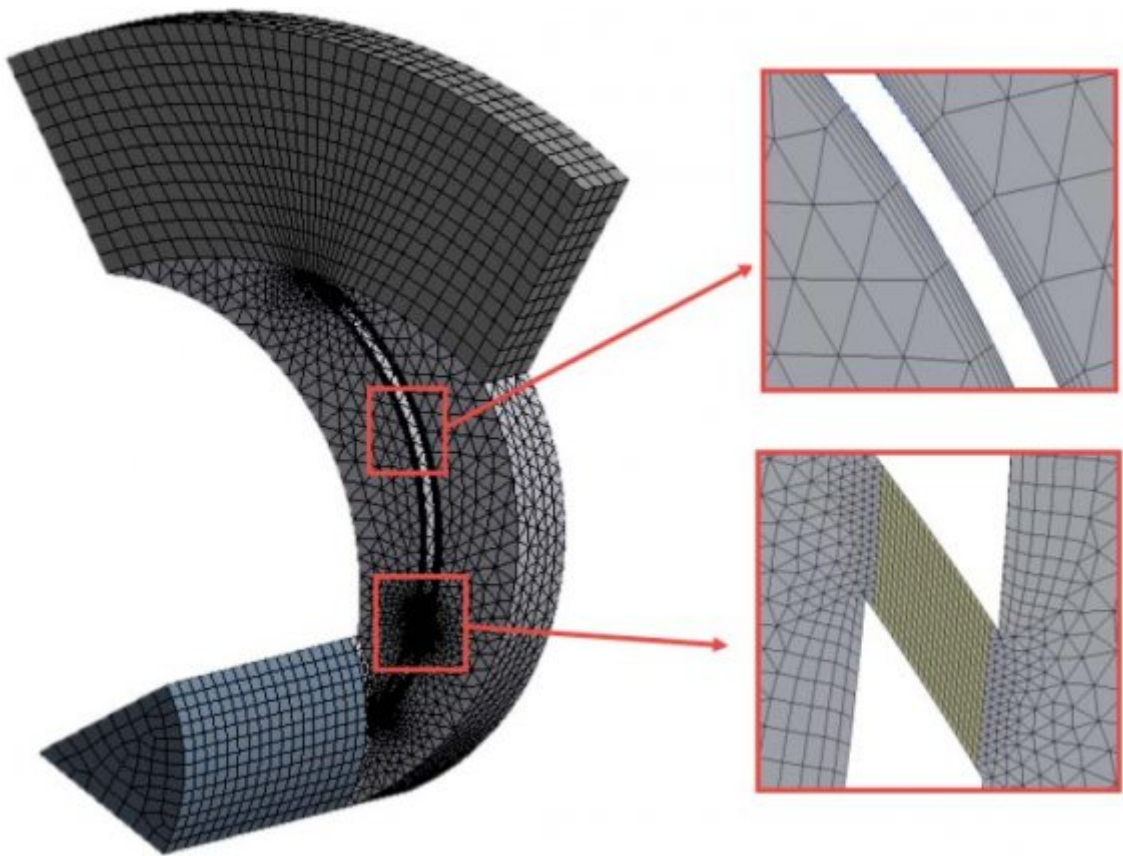
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Figure 3: Figure 3 :



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Figure 4: Figure 4 :Figure 5 :



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Figure 5: Figure ( 6 )

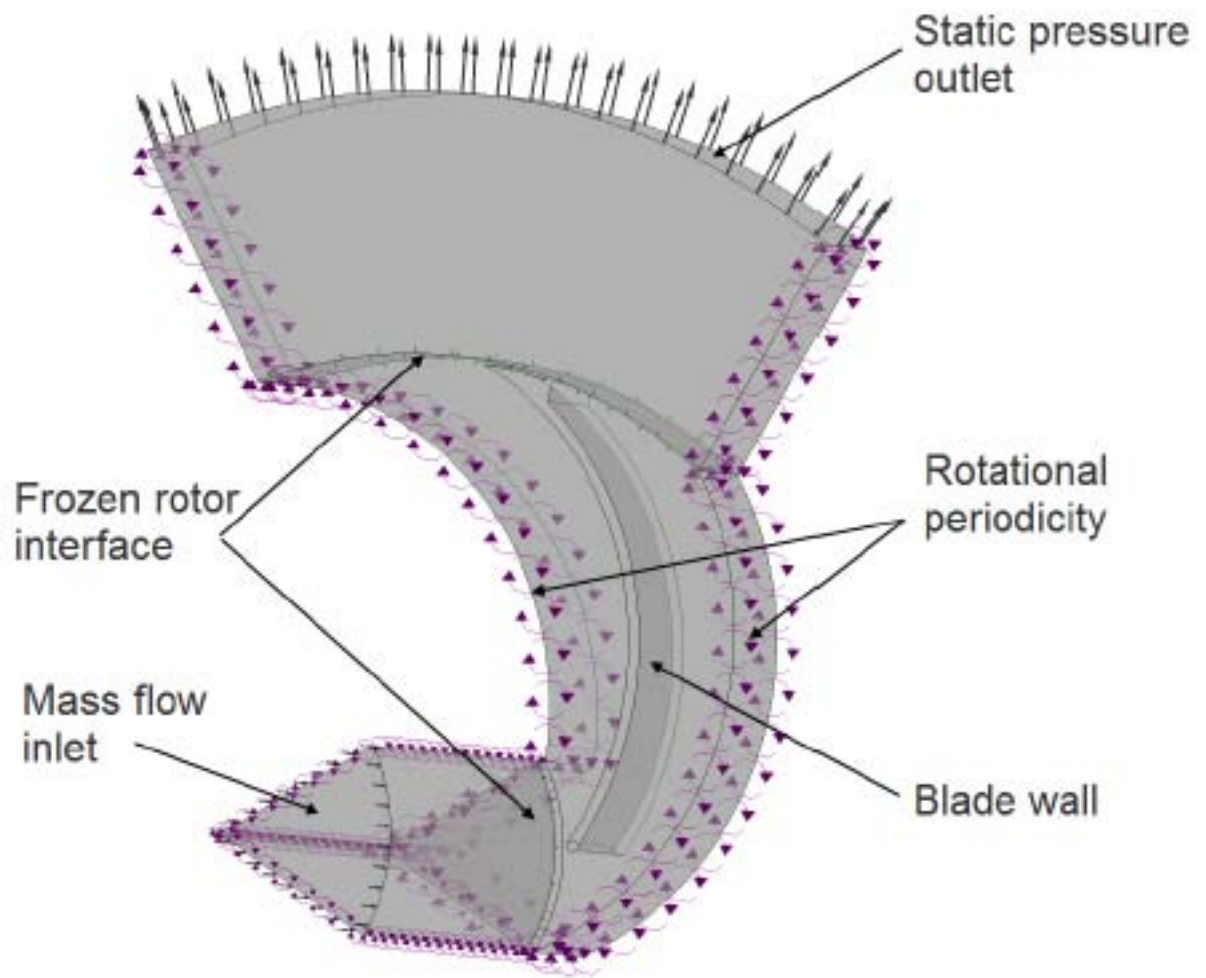
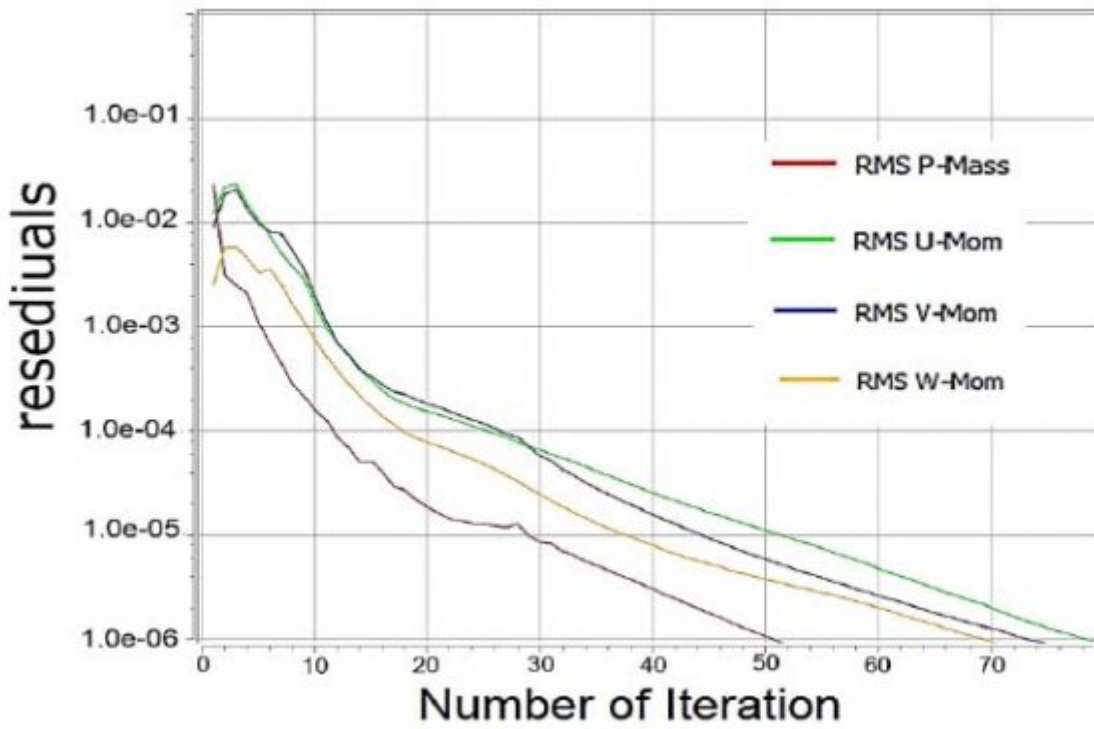
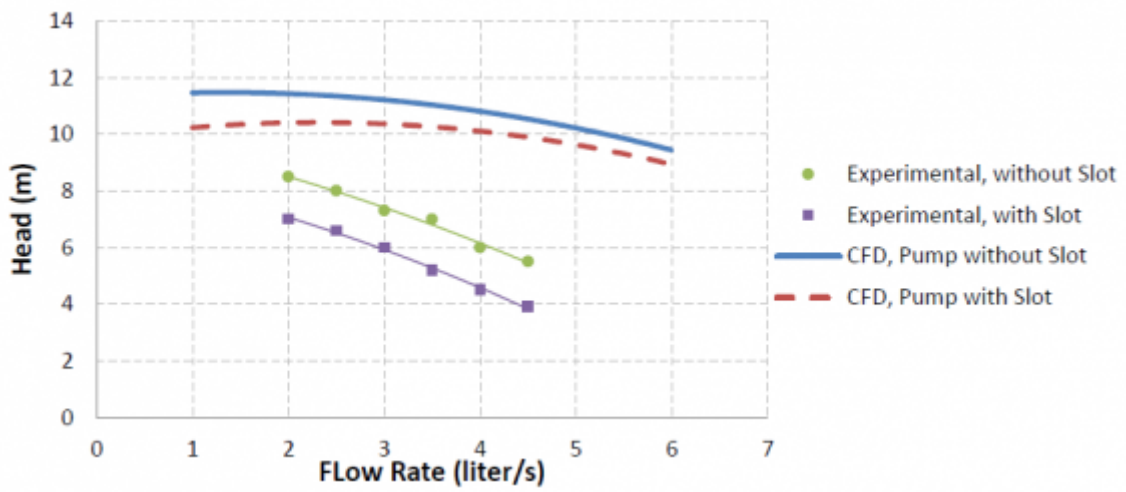


Figure 6: Figure 6 :



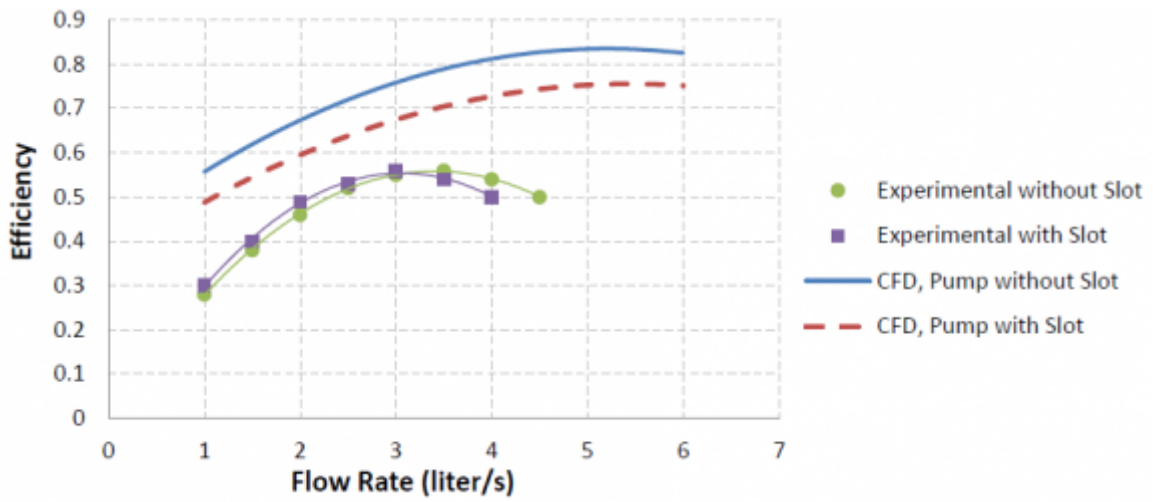
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Figure 7: Figure 7 :



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Figure 8: Figure 8 :



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Figure 9: Figure 9 :

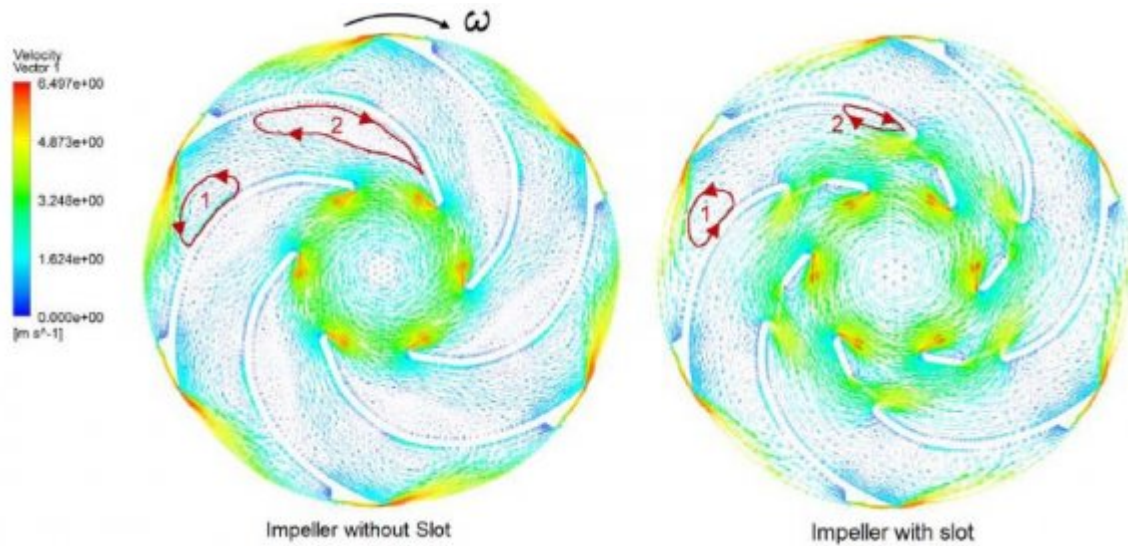
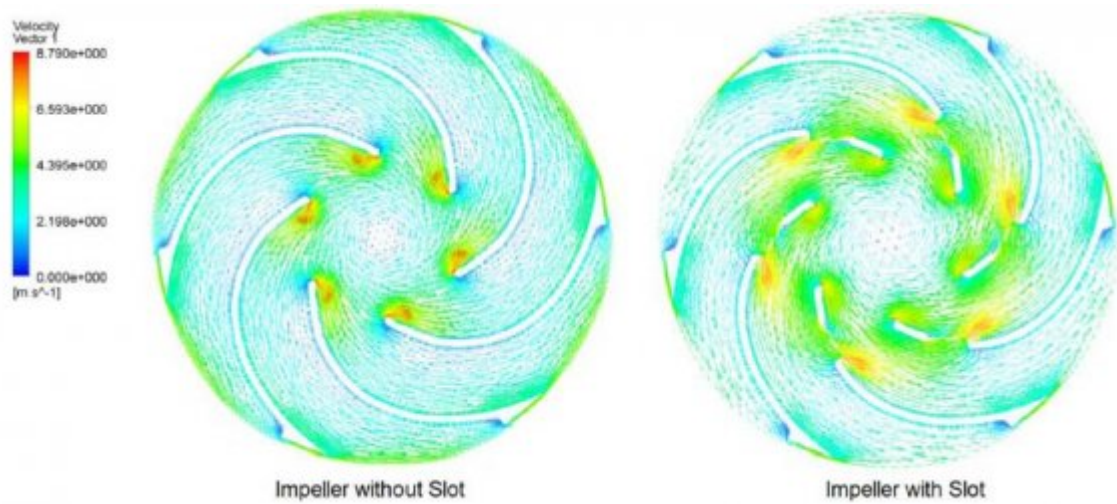
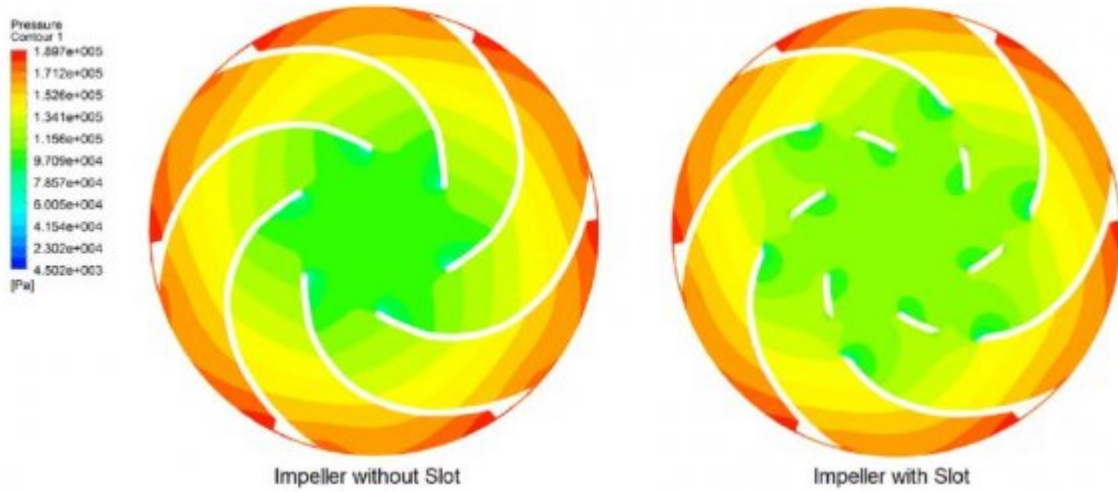


Figure 10:



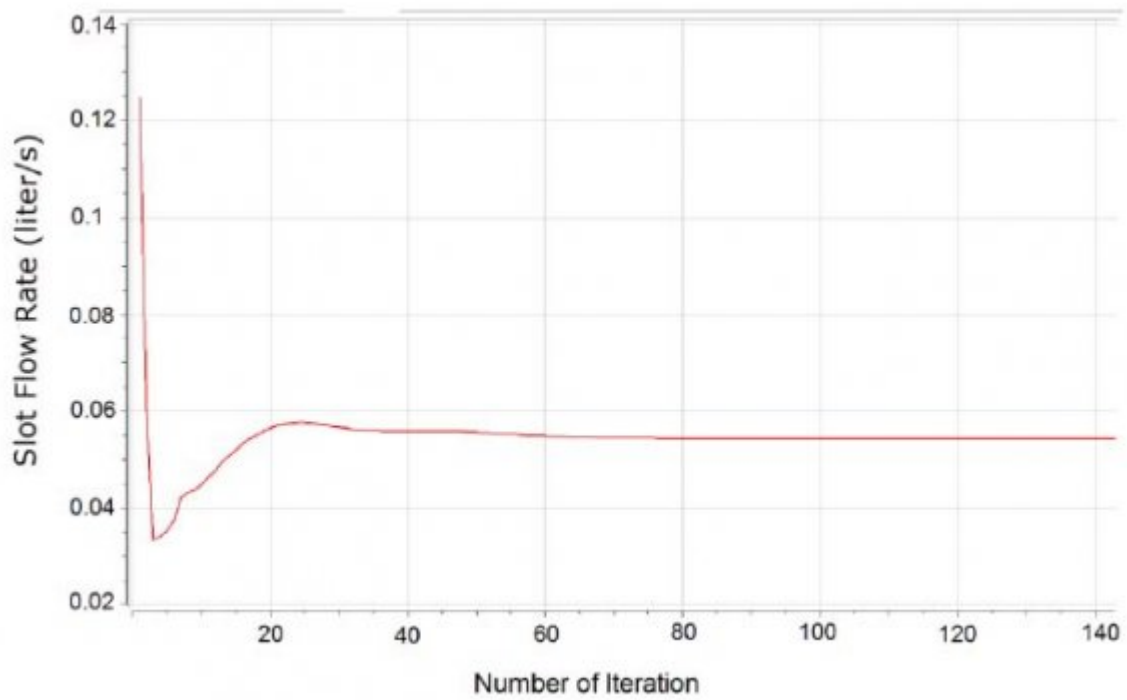
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Figure 11: Figure 10 :



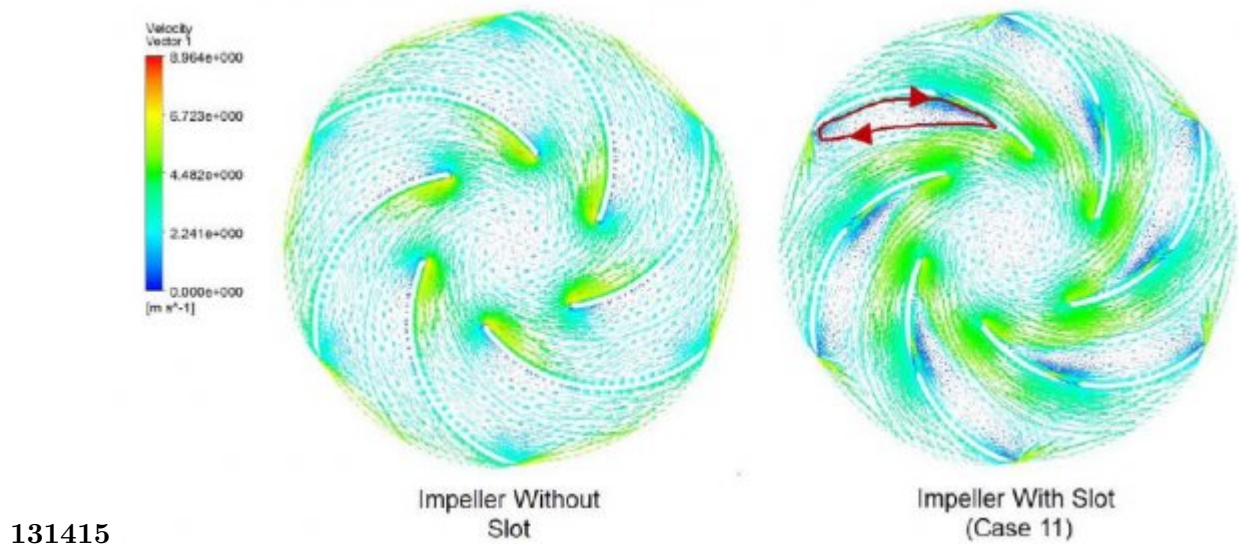
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Figure 12: Figure 11 :



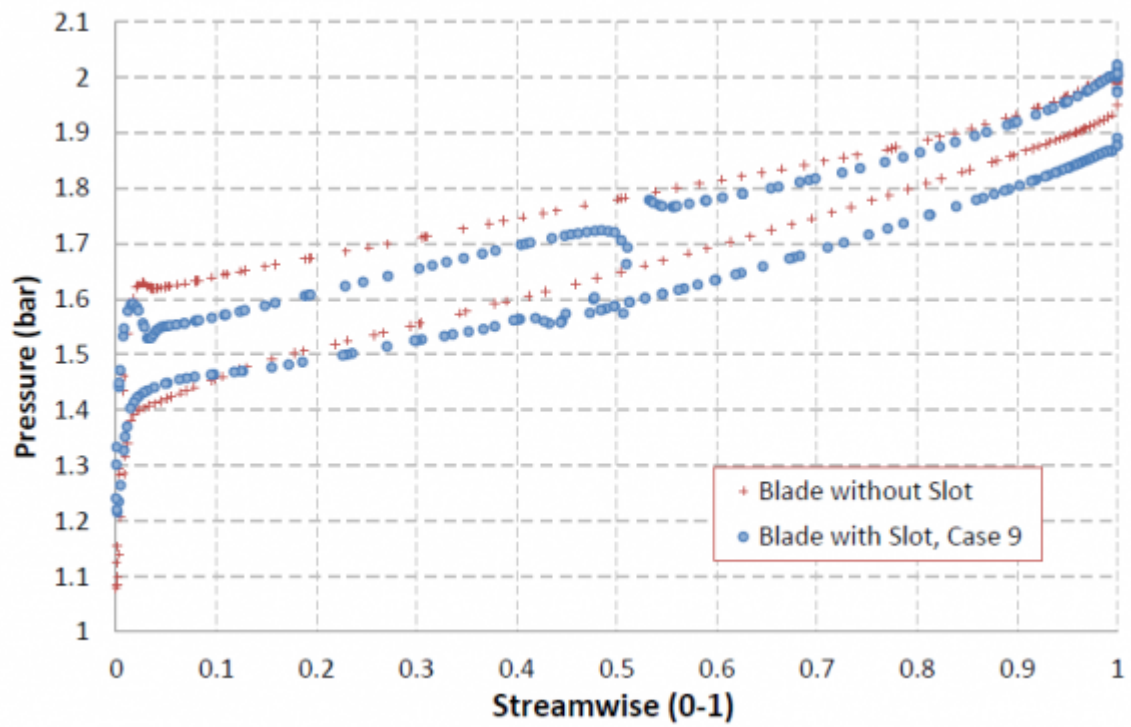
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Figure 13: Figure 12 :



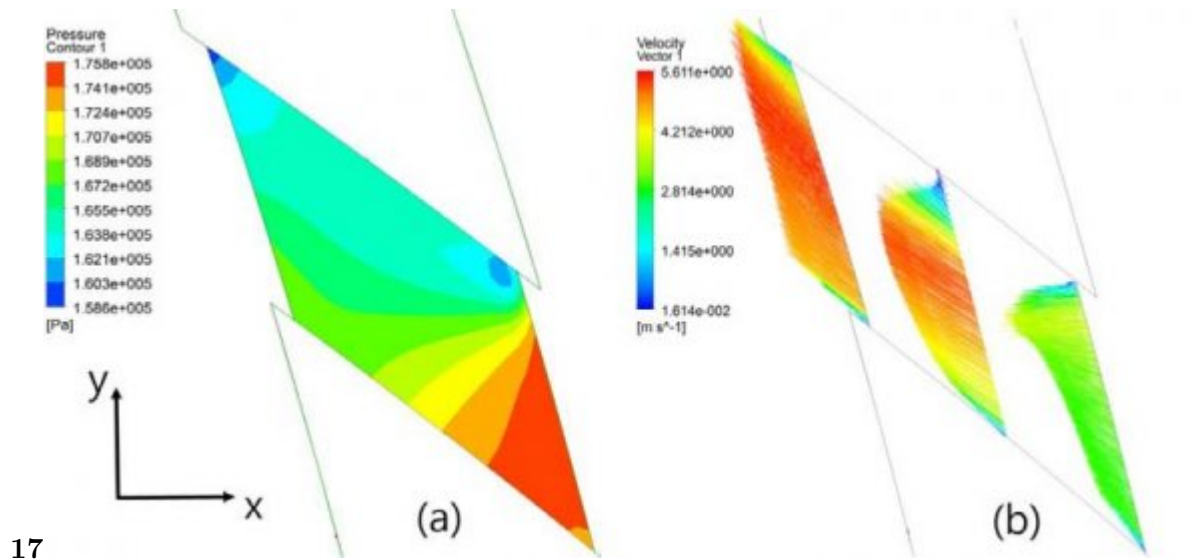
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Figure 14: Figure 13 :Figure 14 :Figure 15 :



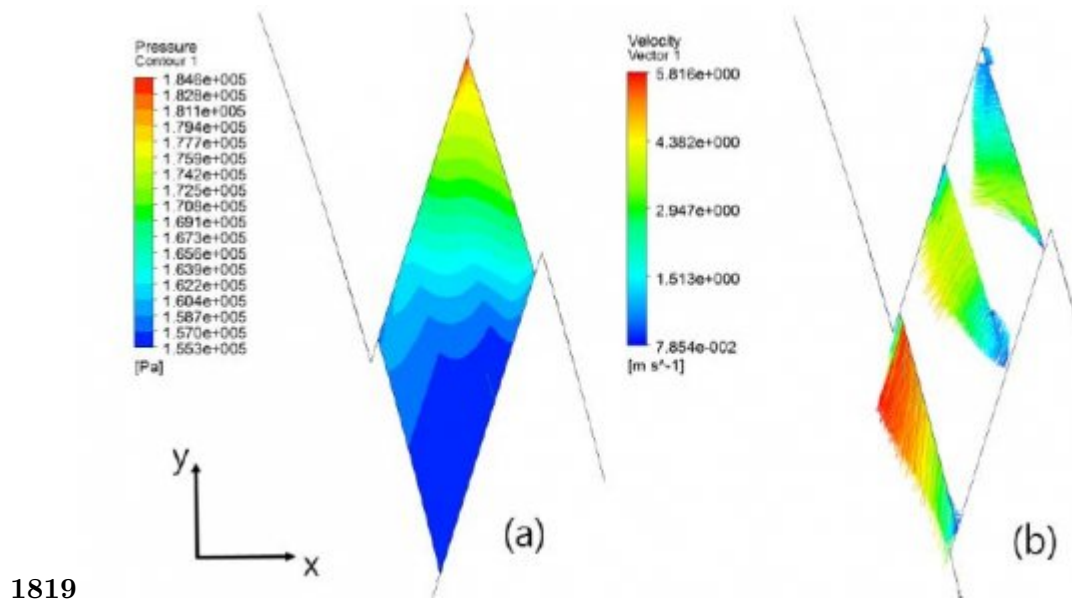
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Figure 15: Figure 16 :



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Figure 16: Figure 17 :



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Figure 17: Figure 18 :Figure 19 :

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Figure 18:

Figure 19:



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