CHAPTER 7

RESULTS AND DISCUSSION: VORTEX GENERATORS

Flow experiments are performed with one and two vortex generators (VGs). They are placed on opposite side, heated side and side walls of the diffuser.

As denoted in chapter 4, the angle made by vortex generators pair is denoted as $\alpha$. The range of $\alpha$ is from $19^\circ$ to $43^\circ$.

Similar to the previous case (protrusion), Nu, efficiency of diffuser, loss coefficient and pressure coefficient for the smooth and rough cases are calculated and analysed. The static pressure is measured on the wall along the diffuser. The stagnation pressures are measured at the grids points of the outlet. Similarly, the temperature is also measured at the grid points as well as on the heated wall.

Correlations are also presented for Nu as a function of Re and geometric parameters which are varied. The correlation is of the form $\text{Nu}=C\text{Re}^m$, with C and m being function of geometric parameters. The variation of C and m is tabulated, as the nature of variation is not simple enough to be expressed as a mathematical function. The Re range is relatively small and for a geometric configuration, only three values of Re are investigated. Hence, the correlations may not be giving the true behaviour in some cases. They have been developed in order to get an overall picture. The r.m.s. error between the correlations and the actual values is less than 5% for all cases.

7.1 One and Two Pair Vortex Generators on Opposite Side

One and two pair vortex generators are placed on the unheated (opposite side) and this effect is investigate. The angle of attack ($\alpha$) varies from $19^\circ$ to $43^\circ$. The top and front view of diffuser roughened by one and two pair VGs is presented in Figs 7.1a to 7.2.
The effect of vortex generators on heat transfer enhancement is presented in Fig. 7.3 and table 7.1. The enhancement increases with angle of attack for all cases. The two pair case exhibits a higher enhancement. As expected, the enhancement decreases with Re. As in the case of protrusions, the Nu ratio decreases with Re. This due to the fact that Nu-rough increases at a slower rate compared to Nu-smooth.

The maximum enhancement is 66% with two pair and 50% with one pair. The enhancement tends to flatten around 45°.

As explained in Gentry et al. [8], there are 2 vortex filaments are generated by a vortex generator, inducing swirl in the flow. In the current case, two adjacent vortex

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**Fig 7.1** Diffuser with a) one pair VGs and b) two pairs VG (top view)

**Fig 7.2** Diffuser with VGs (front view)
filaments from the two vortex generators combine to a form a larger vortex filament as shown in Fig. 7.4. The new vortex filament, being of higher circulation, leads to swirl near the opposite wall as well, leading to increased heat transfer. This is also supported by the fact that the fluid (air) temperature near the heated boundary layer is always higher for the rough case than the smooth one by 2°C. That is, the increased heat transfer caused by the swirl leads to a higher fluid temperature.

The two pair case shows a higher enhancement. This is again due to the additional swirl generated by the second pair. In this case, the fluid temperature in the heated boundary layer is higher than that of the one pair case by 1°C. Thus, the enhancement from one pair to two pairs is not as much as from smooth to one pair. Similarly, a higher angle of attack leads to higher swirl and enhancement. As \( \alpha \) increases, the vortices are closer to the edge of the boundary layer. Thus they have higher momentum and are able to cause more swirl at the heated boundary layer, effecting heat transfer enhancement. This is consistent with the observation of Gentry et al [8].

It is significant that one can get around 62% enhancement even when the vortex generators are located on the opposite (unheated) side. This implies that the swirl effect is strong enough to impart momentum to the boundary layer on the opposite side. The vortex filaments after combining to form a larger one are able to generate swirl on the opposite wall.
Fig. 7.3. Nu ratio at constant Re for one and two pair VGs vs. α (β=5.7°)

Table 7.1 Nu<sub>s</sub>, Nu<sub>1</sub> and Nu<sub>2</sub> vs. Re for selected cases

<table>
<thead>
<tr>
<th>Re</th>
<th>Nu&lt;sub&gt;s&lt;/sub&gt;</th>
<th>Nu&lt;sub&gt;1&lt;/sub&gt; (α=43)</th>
<th>Nu&lt;sub&gt;2&lt;/sub&gt; (α=43)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3E5</td>
<td>647</td>
<td>970</td>
<td>1073</td>
</tr>
<tr>
<td>3.1E5</td>
<td>733</td>
<td>1071</td>
<td>1148</td>
</tr>
<tr>
<td>3.5E5</td>
<td>882</td>
<td>1161</td>
<td>1277</td>
</tr>
</tbody>
</table>

Fig. 7.4 Combination of vortices

As indicated previously, the ratio of Nu for the two pair case with that of one is denoted Nu<sub>2</sub>/Nu<sub>1</sub>. 
The ratio \( \frac{\text{Nu}_2}{\text{Nu}_1} \) at constant \( \text{Re} \) for diffuser 5.7° is presented in Fig 7.5.

![Fig 7.5 Nu ratio (two pair to one pair) for \( \beta=5.7° \)](image)

It can be seen that the enhancement due to the second VGs pair is around 10%. This is consistent with the observation that the increase in air temperature (over the one pair case) is lower than that from the smooth case to one pair. One reason for the lower incremental effect with the second pair may be that the distance between the first and second pairs needs to be increased.

The variation of Nu ratio and Nu as a function of \( \alpha \) at constant \( \text{Re} \) for the \( \beta = 7.0° \) case are shown in Fig. 7.6 and Table 7.2. One can observe that the trend is similar to the previous (\( \beta=5.7° \)) case. The maximum enhancement is slightly lower at 59%. As in the case of protrusions, the Nu values and the Nu ratio is slightly lower than the 5.7° case, due to the increased adverse pressure gradient. As observed in the case of protrusions, the increase in adverse pressure gradient leads to reduced swirl effect. The swirl gets damped by the higher pressure gradient, resulting in lower enhancement.
Fig 7.6 Nu ratio at constant Re for one pair and two pair VG ($\beta=7.0^\circ$)

Table 7.2 $Nu_s$, $Nu_1$ and $Nu_2$ vs. Re for selected cases

<table>
<thead>
<tr>
<th>Re</th>
<th>$Nu_s$</th>
<th>$Nu_1$ ($\alpha=43$)</th>
<th>$Nu_2$ ($\alpha=43$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8E5</td>
<td>649</td>
<td>956</td>
<td>1030</td>
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<tr>
<td>3.1E5</td>
<td>686</td>
<td>993</td>
<td>1063</td>
</tr>
<tr>
<td>3.6E5</td>
<td>796</td>
<td>1037</td>
<td>1108</td>
</tr>
</tbody>
</table>

The ratio $Nu_2/Nu_1$ at constant Re for the diffuser $7.0^\circ$ diffuser is presented in Fig 7.7.
The behaviour is similar to the 5.7° case. As in the case of protrusions, the enhancement is lower, due to the increased adverse pressure gradient. The ratio $\frac{\mathrm{Nu}_2}{\mathrm{Nu}_1}$ is also lower. The first pair is generating vortices in order to get maximum effect from the second pair, it needs to be placed such that it strengthens the vortices further. Thus, the optimum spacing between the pairs needs to be investigated.

### 7.1.2 Heat transfer correlations

Similar to the case of protrusion, the correlation for Nu is given as

$$\mathrm{Nu} = \mathrm{CRe}^m$$

And the correlations for the smooth diffuser are:

- $\mathrm{Nu}_s = 0.148\mathrm{Re}^{0.678}$ for $\beta=5.7^\circ$

and

- $\mathrm{Nu}_s = 0.020\mathrm{Re}^{0.826}$ for $\beta=7.0^\circ$

The variation of C and m with $\alpha$ for one and two pair VGs are shown in Tables 7.3 and 7.4.
Table 7.3 Nu correlation parameters for $\beta=5.7^\circ$

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>one pair</th>
<th>two pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C$</td>
<td>$m$</td>
</tr>
<tr>
<td>19</td>
<td>2.271</td>
<td>0.478</td>
</tr>
<tr>
<td>30</td>
<td>4.067</td>
<td>0.437</td>
</tr>
<tr>
<td>43</td>
<td>6.11</td>
<td>0.410</td>
</tr>
</tbody>
</table>

Table 7.4 Nu correlation parameters for $\beta=7.0^\circ$

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>one pair</th>
<th>two pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C$</td>
<td>$m$</td>
</tr>
<tr>
<td>19</td>
<td>3.139</td>
<td>0.444</td>
</tr>
<tr>
<td>30</td>
<td>6.282</td>
<td>0.395</td>
</tr>
<tr>
<td>43</td>
<td>17.068</td>
<td>0.321</td>
</tr>
</tbody>
</table>

It can be seen from Tables 7.3 and 7.4 that the ‘$C$’ values are higher for the two pair case. This is as expected, as the enhancement is higher. The ‘$m$’ value is slightly lower for two pair case. This is similar to the behaviour observed earlier. In the $\beta = 7.0^\circ$ case, it looks like there are some ‘abnormal’ values, probably due to accumulation of experimental errors.

7.1.3 Comparison heat transfer enhancement based on the diffuser angle

The effect of two pair vortex generators on heat transfer enhancement at constant Re for the diffuser with $\beta=5.7^\circ$ and $7.0^\circ$ is presented in Fig 7.8
One can observe that the enhancement is lower for higher $\beta$. This is as expected as a higher $\beta$ leads to more adverse pressure gradient. This is as observed earlier.

### 7.1.4 Heat transfer enhancement at constant dissipation

The Nu ratio at constant dissipation for the diffuser with $\beta=5.7^\circ$ is shown in Fig 7.9. One can see that the maximum enhancement is 32% for the one pair case and 40% for two pairs. The enhancement increases with the angle of attack. This implies that the heat transfer enhancement effect is significantly more than the increased loss in stagnation pressure. It is also important to note that the enhancement can be achieved even in the case of adverse pressure gradient with the opposite side being roughened. As indicated earlier, the enhancement is due to the swirl induced on the opposite side by the vortex filaments. The vortex filaments are having a significant effect on the opposite side, far away from the roughened boundary layer.
As explained earlier, the ratio of Nu for the two pair case with that of one pair is denoted as \( \frac{Nu_2}{Nu_1} \). The ratio \( \frac{Nu_2}{Nu_1} \) at constant dissipation for diffuser 5.7° is presented in Fig 7.10.

Fig 7.9 Nu ratio at constant dissipation for \( \beta = 5.7° \)

Fig 7.10 Nu ratio (two pair to one pair) at constant dissipation (\( \beta = 5.7° \))
It can be seen that the additional enhancement due to the second pair (at constant dissipation) is around 5%. This implies the enhancement effect of the second pair is almost cancelled by the additional pressure loss.

The Nu ratio at constant dissipation for $\beta = 7.0^\circ$ is shown in Fig 7.11.

![Graph](image_url)

Fig 7.11 Nu ratio at constant dissipation for one and two pair VGs ($\beta=7.0$)

The trend is similar to the $\beta=5.7^\circ$ case. It can be seen that the enhancement is 30% with one VGs pair and 39% with two VG pairs. The enhancement implies that the vortex generator is able to enhance heat transfer effectively, even in the case of adverse pressure gradient.

The ratio $\frac{Nu_2}{Nu_1}$ at constant dissipation for diffuser $7.0^\circ$ is presented in Fig 6.12.
The behaviour is similar to the previous 5.7° case.

### 7.1.5 Comparison heat transfer enhancement based on the diffuser angle

The effect of two pair vortex generators on heat transfer enhancement at constant dissipation for the diffuser with $\beta=5.7^\circ$ and $7.0^\circ$ is shown in Fig 7.13.
For the two pair case, the effect of diffuser angle ($\beta$) is not very significant. This implies that the two pair VGs is able to overcome the effect of adverse pressure gradient.

### 7.1.6 Diffuser efficiency ratio

As outlined earlier the efficiency of the diffuser is defined as

$$\eta_{\text{diff}} = \frac{\text{pressure rise}}{\text{Ideal pressure rise}} = \frac{\Delta P}{\frac{1}{2} \rho V_{\text{in}}^2 - \frac{1}{2} \rho V_{\text{out}}^2} = \frac{p_{\text{out}} - p_{\text{in}}}{\frac{1}{2} \rho V_{\text{in}}^2 - \frac{1}{2} \rho V_{\text{out}}^2}$$

The efficiency ratio is defined as $\frac{\eta}{\eta_s}$, where $\eta_s$ is the smooth diffuser efficiency.

The effect of Re and $\alpha$ on the diffuser efficiency is presented in Figure 7.14 and Table 7.5.

![Fig.7.14 Diffuser efficiency ratio for one pair and two pair VGs ($\beta=5.7^\circ$)](image-url)
Table 7.5 Diffuser efficiency vs. Re for selected cases ($\beta=5.7^\circ$)

<table>
<thead>
<tr>
<th>Re</th>
<th>$\eta_s$</th>
<th>$\eta$ one pair $(\alpha=19^\circ)$</th>
<th>$\eta$ one pair $(\alpha=43^\circ)$</th>
<th>$\eta$ two pair $(\alpha=19^\circ)$</th>
<th>$\eta$ two pair $(\alpha=43^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3E5</td>
<td>0.661</td>
<td>0.498</td>
<td>0.339</td>
<td>0.426</td>
<td>0.330</td>
</tr>
<tr>
<td>3.1E5</td>
<td>0.700</td>
<td>0.483</td>
<td>0.314</td>
<td>0.405</td>
<td>0.302</td>
</tr>
<tr>
<td>3.5E5</td>
<td>0.717</td>
<td>0.455</td>
<td>0.275</td>
<td>0.308</td>
<td>0.224</td>
</tr>
</tbody>
</table>

It can be seen that the diffuser efficiency ratio decreases with the angle of attack. The minimum efficiency ratio is 38% for the one pair case and 31% for the two pairs. This is due to the fact that the VGs generate swirl leading to higher losses. The swirl increases with the angle of attack, leading to more losses. The efficiency ratio is higher at lower Re. Thus, due to the higher enhancement and higher diffuser efficiency, the effectiveness of VGs is more significant at lower Re. The two pair case yields a lower efficiency ratio due to the stagnation pressure losses associated with the additional swirl generated by the second pair.

The behaviour is similar to that encountered in protrusions. As indicated earlier, in the case of protrusions, the efficiency of the smooth case increases with Re, as the boundary layer becomes thinner. In the rough case, the losses become higher with Re. This leads to a slight reduction in efficiency.

The efficiency ratio for the diffuser with $\beta=7.0^\circ$ is given in Fig 7.15. It can be seen that the diffuser efficiency ratio decreases with angle of attack. The minimum efficiency ratio is 38% for the one pair case and 31% for the two pairs. The diffuser efficiency is lower than $5.7^\circ$ case, due to the higher adverse pressure gradient.
For the $\beta=7.0^\circ$ case, the trend is similar to those for $\beta=5.7^\circ$. As expected due to the adverse pressure gradient, the efficiency and efficiency ratios are lower.

The effect of diffuser angle on diffuser efficiency by one and two pair VGs at different $Re$ is shown in Fig 7.16.
One can see that the effect of the second pair is to reduce the efficiency significantly, while the efficiency reduction effect due to $\beta$ is less pronounced. The second pair causes higher losses. Hence, further investigation may be required to optimise the location of the second pair.

### 7.1.7 Diffuser loss coefficient

As presented earlier the loss coefficient of diffuser is obtained as

$$
\zeta = \frac{\text{Loss of stagnation pressure}}{\frac{1}{2} \rho V_{in}^2}
$$

The effect of $\alpha$ and $\text{Re}$ on the diffuser loss coefficient $\zeta$ for the one and two pair VGs ($\beta=5.7^\circ$) is shown in Fig 7.17.
Fig 7.17 Diffuser loss coefficient ratio for one and two pair VGs (β=5.7°)

It can be seen that the ratio of loss coefficient of diffuser increases with Re. The vortex generator leads to an increased loss in stagnation pressure at higher Re, leading to a higher loss coefficient.

The loss coefficient ratio for diffuser with β=7.0° is shown in Fig 7.18.

Fig 7.18 Diffuser loss coefficient ratio for one and two pair VGs (β=7.0°)

The behaviour is similar to the β=5.7° case. The maximum ratio is 2.25.
7.1.8 Pressure coefficient

The comparison of \( C_p \) variation, for the smooth and rough cases for \( \beta = 5.7^\circ \) for one and two pair VGs at different Re, is presented in Fig 7.19. The variation is similar to that of Florian [21].

![Comparison variation of \( C_p \) for one and two pair VGs](image)

Fig 7.19 Comparison variation of \( C_p \) for one and two pair VGs

It can be seen that the smooth case yields the highest value at exit. This is due to the smooth configuration having minimum losses. The loss (as a function of inlet dynamic pressure) decreases with Re. This results in \( C_p \) increasing with Re. The one pair VGs has a higher \( C_p \) than the two pair case due to the former experiencing lower losses.

The variation of \( C_p \) with \( \alpha \) for one pair VGs is shown in Fig 7.20.
As $\alpha$ increases, the pressure losses increase, leading to a lower $C_p$. The smooth case has the highest $C_p$.

The variation of $C_p$ respect to the effect of diffuser angle $\beta$ is given in Fig 7.21.

The diffuser with $\beta=7.0^\circ$ has a higher $C_p$, as the pressure rise is higher.
7.2 One and Two Pair Vortex Generators on Top Side

In this section, the VGs are placed on top (heated) side. The diffuser roughened by one and two pair vortex generators on top (heated) side is shown in Figs 7.22a to 7.23.

![Diagram of diffuser with one pair and VGs (a) and two pairs VGs (top view) (b)]

Fig 7.22 a) Diffuser with one pair and VGs b) Diffuser with two pairs VGs (top view)

![Diagram of diffuser with VGs (side view)]

Fig 7.23 Diffuser with VGs (side view)

The behaviour is similar to the opposite side case discussed previously. As expected, the enhancement is significantly higher here.
7.2.1 Heat transfer enhancement at constant Re

The heat transfer enhancement results are presented in this subsection. As one would expect, they are qualitatively similar to the opposite side case, discussed in the previous section. The enhancement values are significantly higher in the ‘top’ side case discussed below.

The effect of vortex generators on heat transfer enhancement is presented in Fig. 7.24 and Table 7.7.

![Graph showing Nu ratio at constant Re for one pair and two pair VGs (β=5.7°)](image)

**Fig 7.24** Nu ratio at constant Re for one pair and two pair VGs (β=5.7°)

**Table 7.7** Nu, Nu<sub>1</sub> and Nu<sub>2</sub> vs. Re for selected cases (β=5.7°)

<table>
<thead>
<tr>
<th>Re</th>
<th>Nu&lt;sub&gt;s&lt;/sub&gt;</th>
<th>Nu&lt;sub&gt;1&lt;/sub&gt; (α=43)</th>
<th>Nu&lt;sub&gt;2&lt;/sub&gt; (α=43)</th>
</tr>
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<tbody>
<tr>
<td>2.3E5</td>
<td>647</td>
<td>1173</td>
<td>1279</td>
</tr>
<tr>
<td>3.1E5</td>
<td>733</td>
<td>1312</td>
<td>1423</td>
</tr>
<tr>
<td>3.5E5</td>
<td>882</td>
<td>1567</td>
<td>1692</td>
</tr>
</tbody>
</table>

The enhancement increases with angle of attack for all cases. This due to the fact that the vortices are generated closer to the edge of the boundary layer and are able to convert the high thermal gradient fluid. This is consistent with the
observations of Gentry et al. [8]. The two pair case exhibits a higher enhancement. As expected, the enhancement decreases with Re. The maximum enhancement is 81% for one pair VGs and 98% for two pair VGs. The enhancement tends to flatten around 45°. The behaviour is similar to the opposite side case discussed previously. As expected, the enhancement is significantly higher here.

As outlined earlier, the ratio of Nu for two pair case with that of one pair denoted as $\frac{\text{Nu}_2}{\text{Nu}_1}$.

The variation of ratio $\frac{\text{Nu}_2}{\text{Nu}_1}$ at constant Re for the diffuser with $\beta=5.7^\circ$ is shown in Fig 7.25

![Fig 7.25 Nu ratio (two pair to one pair) at constant Re for $\beta=5.7^\circ$](image)

The incremental effect of the second pair diffuser is lower. As explained for the opposite case, this may be due to the spacing between the pairs. The optimum spacing needs to be examined.

The Nu ratio and variation of Nu at constant Re for the $\beta = 7.0^\circ$ case is shown in Fig 7.25 and Table 7.8. One can observe that the trend is similar to the previous case. The maximum enhancement is slightly lower at 93% for two pair VGs and 78% for one pair VGs.
Fig 7.26 Nu ratio at constant Re for one pair and two pair VGs ($\beta=7.0^\circ$)

**Table 7.8** Nu, Nu$_1$, and Nu$_2$ vs. Re for selected cases

<table>
<thead>
<tr>
<th>Re</th>
<th>Nu$_s$</th>
<th>Nu$_1$</th>
<th>Nu$_2$</th>
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<tbody>
<tr>
<td>2.8E5</td>
<td>649</td>
<td>1157</td>
<td>1248</td>
</tr>
<tr>
<td>3.1E5</td>
<td>686</td>
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<td>1303</td>
</tr>
<tr>
<td>3.6E5</td>
<td>796</td>
<td>1361</td>
<td>1474</td>
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</tbody>
</table>

The variation of ratio Nu$_2$/Nu$_1$ at constant Re for the diffuser with $\beta=7.0^\circ$ is presented in Fig 7.27.
The behaviour is similar to the previous case.

**7.2.2 Heat transfer correlation**

Similar to the previous case, the correlation for $\text{Nu}$ is given as

$$\text{Nu} = C \text{Re}^m$$

And the correlations for the smooth diffuser are:

$$\text{Nu}_s = 0.148 \text{Re}^{0.678} \quad \text{for } \beta = 5.7^\circ$$

and

$$\text{Nu}_s = 0.020 \text{Re}^{0.826} \quad \text{for } \beta = 7.0^\circ$$

The variation of $C$ and $m$ with $\alpha$ is shown in Tables 7.9 and 7.10.

**Table 7.9 Nu correlation parameters for $\beta = 5.7^\circ$**

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>one pair</th>
<th></th>
<th>two pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C$</td>
<td>$m$</td>
<td>$C$</td>
</tr>
<tr>
<td>19</td>
<td>0.474</td>
<td>0.624</td>
<td>0.880</td>
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<tr>
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<td>0.493</td>
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<td>1.097</td>
</tr>
<tr>
<td>43</td>
<td>0.731</td>
<td>0.595</td>
<td>0.632</td>
</tr>
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</table>

![Graph](image_url)
Table 7.10 Nu correlation parameters for $\beta=7.0^\circ$

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>one pair</th>
<th>two pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C$</td>
<td>$m$</td>
</tr>
<tr>
<td>19</td>
<td>0.199</td>
<td>0.683</td>
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<td>0.034</td>
<td>0.823</td>
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<td>43</td>
<td>0.251</td>
<td>0.671</td>
</tr>
</tbody>
</table>

One can see from Tables 7.9 and 7.10 that the two pair case has a higher ‘$C$’ and lower ‘$m$’ for $\beta=5.7^\circ$. This is consistent with the fact that the effect of second pair diminishes with Re. In the one pair case, the value of ‘$m$’ is close to that of the smooth case. This implies that the effect of VGs will not decrease rapidly with Re. The behaviour is similar for $\beta=7.0^\circ$. It looks like there are a few ‘abnormal’ points here as well.

7.2.3 **Comparison heat transfer enhancement based on the diffuser angle**

The effect of diffuser angle on Nu ratio at constant Re is presented in Fig 7.28

![Fig 7.28 Nu ratio vs. $\alpha$ for different $\beta$](image-url)
It is seen that the Nu ratio drops slightly for the $\beta = 7.0^\circ$ diffuser. This is similar to what has been observed earlier. The decrease is slightly lower for the two pair case.

### 7.2.4 Heat transfer enhancement at constant dissipation

The Nu ratio at constant dissipation for the diffuser with $\beta=5.7^\circ$ is shown in Fig 7.29. One can see that the maximum enhancement is 58% for the one pair case and 70% for two pairs. The enhancement increases with angle of attack. This implies that the heat transfer enhancement effect is significantly more than the increased loss in stagnation pressure. The enhancement tends to flatten around 45°.

![Fig 7.29 Nu ratio at constant dissipation for one and two pair VGs $\beta=5.7^\circ$](image)

The variation of ratio $Nu_2/Nu_1$ at constant dissipation for the diffuser with $\beta=5.7^\circ$ is shown in Fig 7.30.
The additional enhancement due to the second pair is between 7-9%.

The Nu ratio at constant dissipation for $\beta=7.0^\circ$ is shown in Fig 7.31. The trend is similar to the $\beta=5.7^\circ$ case. It can be seen that the enhancement is 53% with one VGs pair and 64% with two VG pairs. The enhancement implies that the vortex generator is able to enhance heat transfer effectively, even in the case of adverse pressure gradient.

Fig 7.31 Nu ratio at constant dissipation for one and two pair VGs $\beta=7.0^\circ$
The variation of ratio $\frac{\Nu_2}{\Nu_1}$ at constant dissipation for the diffuser with $\beta=7.0^\circ$ is shown in Fig 7.

![Graph showing the variation of ratio $\frac{\Nu_2}{\Nu_1}$](image)

Fig 7.32 Nu ratio (two pair to one pair) at constant Re for $\beta=7.0^\circ$

The additional enhancement of the second pair drops with $\alpha$. Thus, one needs to investigate the case where the first and second pairs have different angles of attack, in order to obtain the optimum configuration.

**7.2.5 Effect of diffuser angle on heat transfer**

The effect of diffuser angle on Nu ratio at constant dissipation is shown in Fig 7.33.
The behaviour is as expected, with the 7.0° diffuser yielding a (5%) lower enhancement.

7.3 One and Two Pair Vortex Generators on Vertical Side Walls

In this section, the VGs are placed on the two vertical side walls. As before, the top wall is heated. The side wall roughened diffuser is shown in Figs 7.34a to 7.35.

Fig 7.33 Nu ratio at constant dissipation for the different angle of diffuser

Fig 7.34 Diffuser with a) one pair VGs and b) two pairs VGs (front view)
7.3.1 Heat transfer enhancement at constant Re

The effect of vortex generators on heat transfer enhancement is presented in Fig 7.36 and Table 7.11. The behaviour is qualitatively similar to the cases where the opposite side or top sides are roughened. The enhancement increases with the angle of attack. The enhancement is in between the top and opposite cases. This is also as expected, as the swirl effect is more than that of the opposite case. The top rough case has shown yields the maximum enhancement as that is the heated surface. As expected, the enhancement decreases with Re. The maximum enhancement is 67% for one pair VGs and 83% for two pair VGs.

The enhancement is lower than the top side case because the VGs are outside the boundary layer.

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**Fig 7.36 Nu ratio at constant Re vs. α (β=5.7°)**
Table 7.11 Nuₘ, Nu₁ and Nu₂ vs. Re for selected cases

<table>
<thead>
<tr>
<th>Re</th>
<th>Nuₘ</th>
<th>Nu₁ (α=43)</th>
<th>Nu₂ (α=43)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3E5</td>
<td>647</td>
<td>1080</td>
<td>1184</td>
</tr>
<tr>
<td>3.1E5</td>
<td>733</td>
<td>1183</td>
<td>1215</td>
</tr>
<tr>
<td>3.5E5</td>
<td>882</td>
<td>11393</td>
<td>1514</td>
</tr>
</tbody>
</table>

The ratio of Nu₂ /Nu₁ at constant Re for the diffuser with β=5.7° is presented in Fig 7.37. As in previous cases of opposite and top side roughening the incremental effect of the second pair is lower.

Fig 7.37 Nu ratio (two pair to one pair) at constant Re vs. α for β=5.7°

The Nu ratio at constant Re for the β = 7.0° case is shown in Fig 7.38 and table 7.12. One can observe that the trend is similar to the previous case. The maximum enhancement is slightly lower at 79% for two pair VGs and 63 % for one pair VGs.
Fig 7.38 Nu ratio (two pair to one pair) at constant Re vs. α for β=7.0°

Table 7.12 Nu₂, Nu₁ and Nu₂ vs. Re for selected cases

<table>
<thead>
<tr>
<th>Re</th>
<th>Nu₅</th>
<th>Nu₁ (α=43)</th>
<th>Nu₂ (α=43)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8E5</td>
<td>649</td>
<td>1058</td>
<td>1162</td>
</tr>
<tr>
<td>3.1E5</td>
<td>686</td>
<td>1089</td>
<td>1181</td>
</tr>
<tr>
<td>3.6E5</td>
<td>796</td>
<td>1298</td>
<td>1401</td>
</tr>
</tbody>
</table>

The variation of ratio Nu₂ /Nu₁ at constant Re for the diffuser with β=7.0° is presented in Fig 7.39. The behaviour is similar to the previous (β=5.7°) case.
The additional enhancement due to the second pair is from 8-10%. This is similar to the opposite and top side roughened cases.

### 7.3.2 Effect of diffuser angle on heat transfer

The effect of diffuser angle on Nu ratio at constant Re is presented in Fig 7.40.

![Fig 7.40 Nu ratio vs. α (at constant Re) for different β](image)
As outlined earlier the enhancement is lower for $\beta=7.0^\circ$.

**7.3.3 Heat transfer enhancement at constant dissipation**

The Nu ratio at constant dissipation for the diffuser with $\beta=5.7^\circ$ is shown in Fig 7.41.

![Graph showing Nu ratio at constant dissipation](image)

Fig 7.41 Nu ratio at constant dissipation for one and two pair VGs $\beta=5.7^\circ$

One can see that the maximum enhancement is 41% for the one pair case and 57% for two pairs. The enhancement increases with angle of attack. The trend is similar to that of the opposite or top side roughened case.

The Nu ratio at constant dissipation for $\beta=7.0^\circ$ is shown in Fig. 7.42. The trend is similar to the $\beta=5.7^\circ$ case.
It can be seen that the enhancement is 41% with one VGs pair and 55% with two VG pairs.

**7.3.4 Effect of diffuser angle on heat transfer**

The effect of diffuser angle on Nu ratio at constant dissipation is presented in Fig 7.43.
The behaviour is similar to the previous at constant Re.

7.4 Summary

Similar to protrusions, VGs too exhibit significant heat transfer enhancement even when the opposite (unheated) side is roughened. As with protrusions, the two pair yields a higher enhancement. The same is with top side cases.

When the opposite (unheated) side is roughened, the maximum enhancement at constant Re is 50% with one pair and 66% with two pairs. At constant dissipation, the corresponding values are 32% and 40%. For the case where the top (heated) side is roughened, the enhancement values at constant Re are 77% (one pair) and 98% (two pairs). The corresponding values at constant dissipation are 58% and 70%.

In the case of top side roughening, the exponent of Re is almost the same as that of the smooth case. This tends to imply that the effect of enhancement diminishing with Re is not that significant when the top side is roughened with VGs.