Optimisation of wastegate bypass flow reintroduction for increased turbine stage efficiency

C. Hasler
Cummins Turbo Technologies – Advanced Technology Dept, England

ABSTRACT

A significant proportion of modern turbochargers incorporate a wastegate system into their architecture. This system allows the bypassing of flow around the turbine wheel to prevent an over-boosted engine condition. CTT has identified that while the wastegate is in its open position there are several key design changes which can be made in order to greatly increase turbine stage efficiency.

This paper discusses the pitfalls of current wastegate turbine design, highlighting the areas for its improvement. Three key parameters were studied and are discussed in detail: flow reintroduction angle, the method of flow reintroduction and wastegate bypass capability. Through a combination of computational analysis and test work, this paper quantifies the benefits of each of these parameters and the overall improvement to wastegated turbine stage design.

1 INTRODUCTION

In certain applications, the turbine housing is sized to improve low expansion ratio (ER) performance. This can lead to over-speeding of the compressor and over-boosted engine conditions at higher turbine ERs. In order to avoid this, a wastegate port is used to bypass a percentage of the exhaust flow around the turbine wheel reducing the available energy and therefore the shaft power. [1]

The bypass flow is directed through a port in the volute into a cavity downstream of the turbine wheel exducer. The method in which this bypass flow is reintroduced can have a strong effect on the efficiency of the turbine stage. As the flow passes between the port and wastegate valve it is accelerated and if not directed correctly can cause an aerodynamic blockage to the bulk flow leaving the turbine wheel. Efficiency losses to the turbine stage which are caused by this disruption are described as wastegate flow mixing losses. It is the aim of this paper to identify and characterise the key parameters which govern the interactions causing these losses and from this new understanding, to minimise them.

A turbine is required to provide a set amount of power to the compressor at a fixed shaft speed and if too much power is being generated, the wastegate is opened. If one stage is more efficient than another it produces more work. Reductions to mixing losses increase the wastegate-open turbine stage efficiency. This will then cause the wastegate to be opened more, reducing the pumping work during the exhaust stroke and thus reducing the fuel consumption of the engine [2].

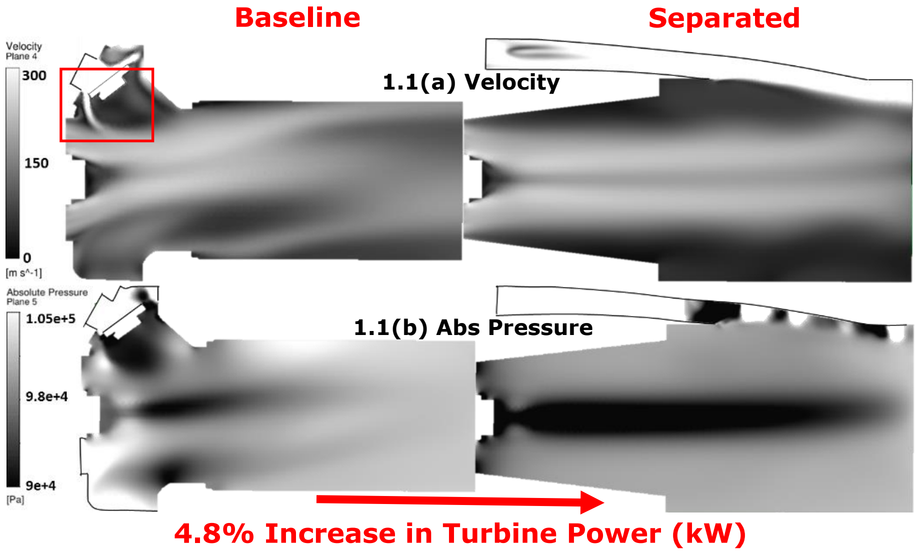


Figure 1.1 – Wastegate flow reintroduction contours (upper - velocity & lower – static pressure) [ER = 3, 70kRPM]

Comparing the baseline to a design which separates the wastegate flow, reintroducing it far downstream (3 pipe diameters), allows us to understand the issues with the conventional method. This method replicates the work done by J.Yang and T.Campbell which demonstrates a significant decrease in on engine BSFC [3]. High-velocity flow is seen in Figure 1.1(a) as white. Observing the highlighted, boxed region there is a high-velocity jet of exhaust gas passing into the bulk flow. This causes a region of low static pressure (dark in Figure 1.1(b)) behind it. An area of high pressure can be seen on the opposing side of the wheel. The pressure differential here pulls the flow towards the wastegate port. This disruption gives an overall increase in the static pressure at the outlet of the turbine wheel. Contrasting this against the low pressure at the wheel outlet of the right-hand model, the key to improve wastegate-open turbine stage performance becomes apparent.

A stage with poor wastegate bypass flow reintroduction and thus high mixing losses causes a high back pressure on the wheel outlet. This decreases the ER across the wheel and in turn reduces the available energy the wheel has to extract for the same inlet conditions. Therefore there is a reduction in wastegate-open turbine stage efficiency [4]. This is the main driver for the poor efficiency seen on the baseline and thus is a big lever for increasing performance.

2 METHOD

Although both full turbine stage computational fluid dynamics (CFD) and test work are used as analytical methods throughout this paper, CFD is used more heavily due to the cost and time-saving implications. As such it is critical that the setup and methodology used are representative of testing on a dynamometer.

In order to ensure this, the CFD setup was first proven by replicating a real-life test case. Two turbocharges were mapped on the dynamometer at CTT to enable calibration of the full turbine stage CFD model. The conditions experienced by the turbine were applied to the model, i.e. pressure, temperature and wheel speed. The resulting analysis showed that the trends in turbine stage efficiency and stage mass flows correlated well with the results from the turbine map. This gives us the confidence to use this setup throughout the studies shown in this paper. Similar such comparisons can be seen in Figures 4.2 and 4.3.

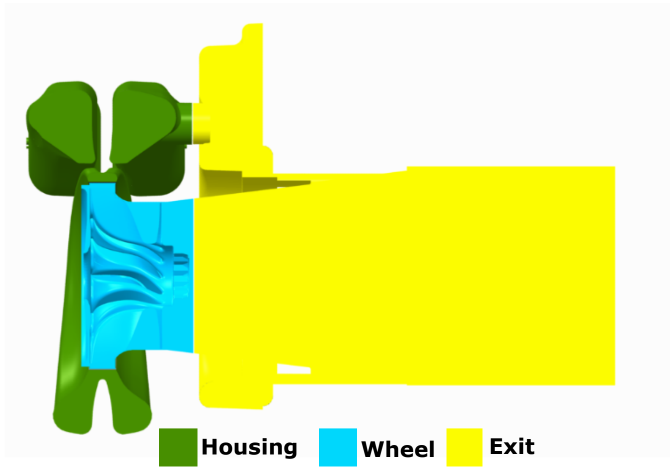


Figure 2.1 – Full stage CFD model

The full stage CFD used has three distinct regions: housing, wheel and exit. Each of these sections is meshed to a level which allows good CFD convergence but does not waste computational time. The wastegate flow reintroduction occurs within the exit region, for this reason, it is the main focus throughout this paper.

3 STUDY I – FLOW REINTRODUCTION ANGLE

The angle at which the bypass flow is reintroduced (the angle of mixing) has a significant effect on turbine stage efficiency. In order to validate and quantify this theory, a full stage CFD study was created. A number of cavity models were generated to vary the angle of mixing.

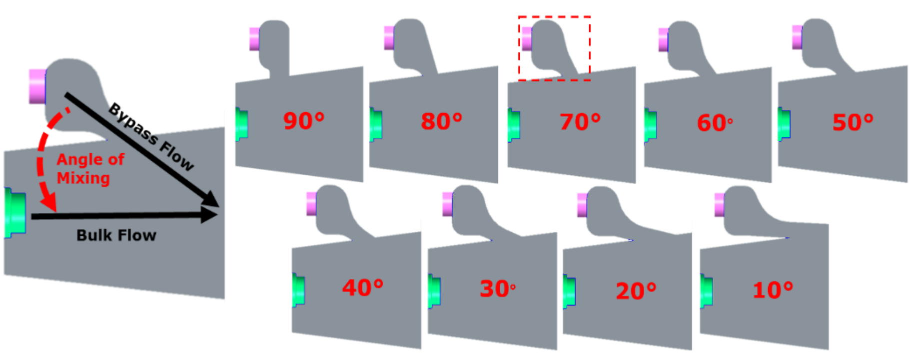


Figure 3.1 – Angle of mixing diagram (left) and cavity models with decreasing angle of mixing (right)

The aim of this study was to simulate a turbine stage under both wastegate-open and wastegate-closed conditions in order to fully understand the effect that the flow reintroduction has on the turbine stage. In order to ensure accurate results the previously proven CFD methodology was applied to this case. To reduce computational time, only a few of the reintroduction angles were selected for the wastegate-closed analysis.

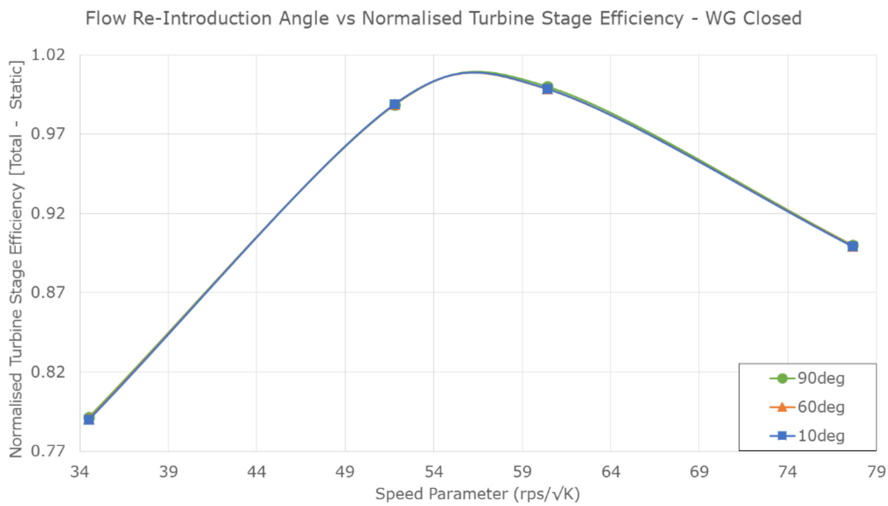


Figure 3.2 – Wastegate-closed flow reintroduction results (Selected angles) [ER = 3]

Note that all lines lie on top of one another, this shows that there is no difference between each of the models in the wastegate-closed analysis. This is likely due to the fact that the total pressure in the wastegate cavities (highlighted region in Figure 3.1) is equal to that of the static pressure in the diffuser. As such, there is no pressure differential to encourage flow into this area, this means there is little disruption caused by the flow reintroduction port.

This is an important result, although application dependent, the majority of running conditions for a diesel engine are more heavily weighted towards wastegate-closed conditions. The highest percentage of time is spent at a lower compressor speed [5] where turbo over-speeding is not an issue and therefore the wastegate is closed. As such any losses to turbine stage efficiency in these conditions can outweigh gains when the wastegate is open.

The next step is to analyse each of the models in wastegate-open conditions. Here we should see the effect of varying the flow reintroduction angle. As the bypass flow re-joins the bulk flow, the angle of mixing between the two flows has an effect on the efficiency of the stage as a whole. It is theorised that the higher the angle of mixing the lower the efficiency.

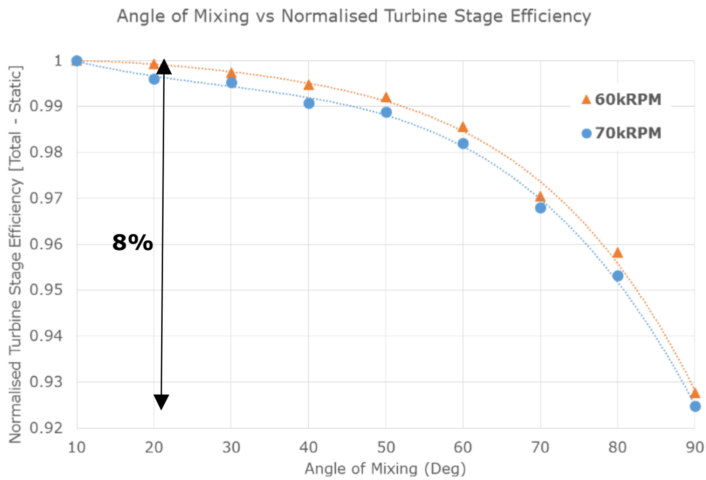


Figure 3.3 – Wastegate-open flow reintroduction results (Selected turbo speeds) [ER = 3]

A well-defined trend is clearly present in Figure 3.3. From this, it can be suggested that the greatest proportion (around 75%) of the benefit can be gained from turning the angle of mixing from 90° to 60°. Diminishing gains, although still significant, are then available as the flow is then turned through the last 50°.

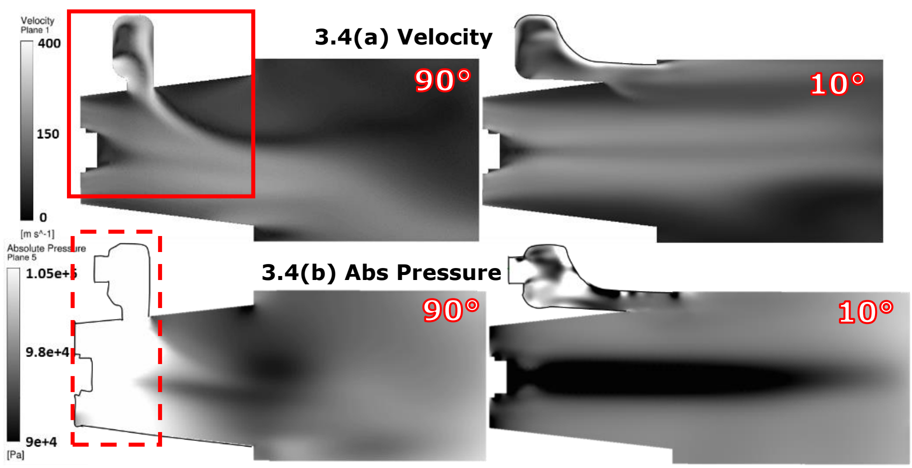


Figure 3.4 – Wastegate flow reintroduction contours (upper - velocity & lower – static pressure) [ER = 3, 70kRPM]

Observing Figure 3.4, the comparison between the passage of the bulk flow of the two models as the bypass flow is reintroduced suggests as to the primary cause of increased loss. The wastegate flow jets out of the 90° reintroduction port (solid boxed region) causing a localised aerodynamic blockage. The bulk flow meets a high-velocity wall of flow which diverts its progression causing significant losses and an increase in static pressure (dashed boxed region). This increase in back pressure has an adverse effect on the performance of the stage as discussed in Section 1. This image then shows that the angle at which the bypass flow is reintroduced is critical in minimising the static pressure at the turbine outlet.

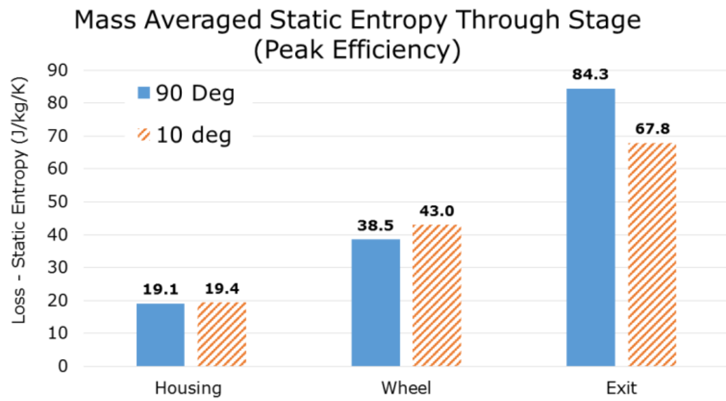
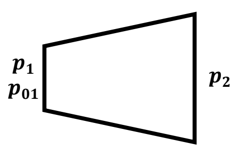


Figure 3.5 – Stage loss breakdown (static entropy) [ER = 3, 70kRPM]

The disruption caused by the high-velocity flow is again shown through the stage loss breakdown in Figure 3.5. Here there is a significant increase in the static entropy in the exit region (wheel outlet to diffuser outlet) of the 90° reintroduction model. This can be attributed to two things. Firstly the aerodynamic losses caused by the blockage of the bulk flow from the bypass flow and secondly the reduction in diffuser effectiveness. Diffuser effectiveness (η_D) is defined below [6].

$$\eta_D = C_p / C_{p,ideal} \qquad C_p = \frac{p_2 - p_1}{p_{01} - p_1} \qquad C_{p,ideal} = 1 - 1/AR^2$$



η_D	Diffuser effectiveness
C_p	Coefficient of static pressure recovery
$C_{p,ideal}$	Ideal coefficient of static pressure recovery
p_1	Diffuser inlet static pressure
p_{01}	Diffuser inlet total pressure
p_2	Diffuser outlet static pressure
AR	Diffuser area ratio (outlet/inlet area)

Table 3.1 – Nomenclature for diffuser effectiveness calculation

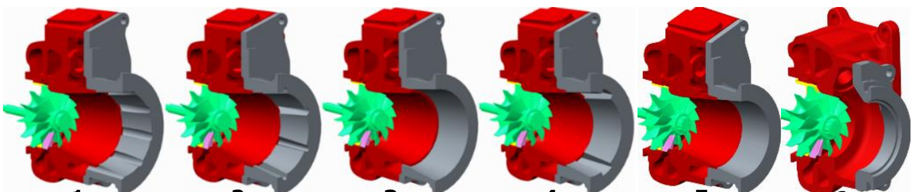
Diffuser effectiveness is reduced through a combination of two effects. Firstly an increase in the diffuser inlet static pressure (p_1) as shown in Figure 3.4, this reduces the coefficient of static pressure recovery (C_p). The second effect is the reduction in pressure recovery due to flow separation from the diffuser walls caused by the aerodynamic blockage.

All of this data concludes that if one wishes to increase wastegate-open turbine stage efficiency it is critical that any bypass flow should be reintroduced with the minimum angle of mixing to the bulk flow. This both improves the ER across the wheel and the diffuser effectiveness. A small angle of mixing can be achieved through the turning of the bypass flow to be collinear to the flow leaving the turbine wheel. With this in mind, the next section moves to study the effect of the reintroduction port shape itself.

4 STUDY II – FLOW REINTRODUCTION PORT SHAPE

Study II aims to demonstrate an optimum concept for the bypass flow reintroduction and understand the sensitivity that flow reintroduction port design has on turbine stage efficiency. An optimum design is defined as one which reduces wastegate flow mixing losses without impacting the wastegate-closed turbine stage efficiency.

The previous study concluded that the more collinear the bypass flow reintroduction to the bulk flow, the higher the wastegate-open turbine stage efficiency. Thus an optimum flow reintroduction port would be angled such that it will turn the flow to follow the bulk flow. Four concepts were chosen for analysis, each with a different shape of reintroduction port but with the same flow angle. It should be noted that concept 3 follows the design guidelines set out in [7].



Concept	Description	Concept	Description	Concept	Description
1	Straight bore holes	3	Circumferential slot	5	Ideal Diffuser
2	Steep angled circular slots	4	Large rectangular slots	6	Current Product

Figure 4.1 – Flow reintroduction port design concepts

As in Study I, both wastegate-open and closed turbine stage conditions were simulated in full stage CFD. This grants us the ability to understand if a concept qualifies for both of the criteria required for an optimum design. In addition, for each concept, prototype hardware was created and tested on the turbine dynamometer at CTT Huddersfield. This gives a direct comparison between the CFD simulation and test, further validating any results produced.

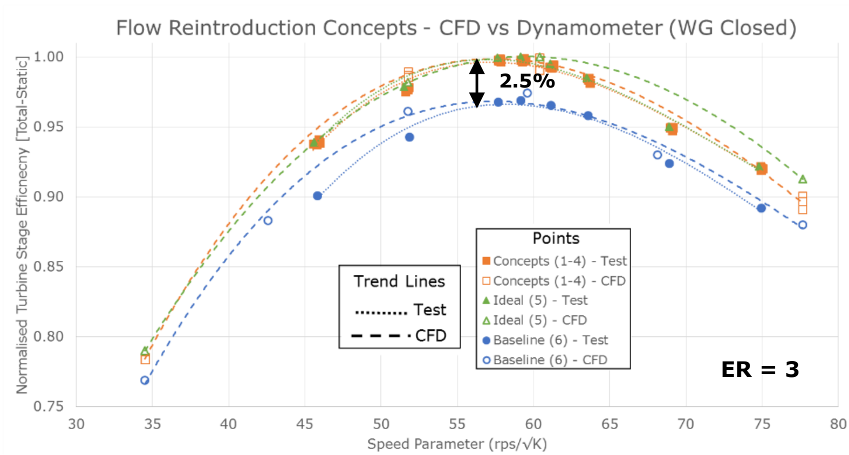


Figure 4.2 – Flow reintroduction port design wastegate closed results

An optimum design requires a minimal reduction in wastegate-closed turbine stage efficiency. In order to quantify any loss to this parameter, each concept was compared to a model which has no flow reintroduction ports interrupting the diffuser and thus is optimum for this geometry. Figure 4.2 demonstrates that each of the concepts is not only indistinguishable from one another but also from the ideal case. This means that none of the flow reintroduction port designs causes degradation to the diffuser effectiveness as set out in Section 3. It should be noted that the increase in efficiency from the baseline is due to the addition of a turbine diffuser as explained in [8]. The CFD and test data are both normalised from their respective highest result, there is a delta in their absolute values. When normalised there is a good correlation between CFD and test data solidifying the CFD methodology and the result.

The second component of an optimum bypass flow reintroduction design is that it reduces the wastegate flow mixing losses. The simplest way to quantify this is through the turbine stage efficiency under wastegate-open conditions. As the wastegate is opened, instead of a reduction in flow to the turbine as seen on engine (constant mass flow), more flow is passed through the stage (constant ER). Thus if there is a flow discrepancy between any of the concepts then the turbine stage efficiency equation [4] should not be used due to a change in the available energy passing through the stage. So instead of stage efficiency, the power produced by the turbine wheel can be used as a comparative method for a fixed ER and turbine inlet temperature.

This may even be a more useful way to visualise wastegate-open results. As discussed in the introduction the turbine is required to provide a set amount of power to the compressor at a fixed shaft speed. When the turbine is providing too much power the wastegate is opened more. Thus reductions in mixing loss which equate to an increase in turbine power require a higher percentage of wastegate bypass. This reduces the back pressure on the engine. Therefore if an increase in power is observed on the dynamometer it would equate to a reduction in pumping work for the engine and thus a reduction in fuel consumption. The decrease in turbine inlet pressure due to increased valve opening for a more efficient stage is also shown in [9].

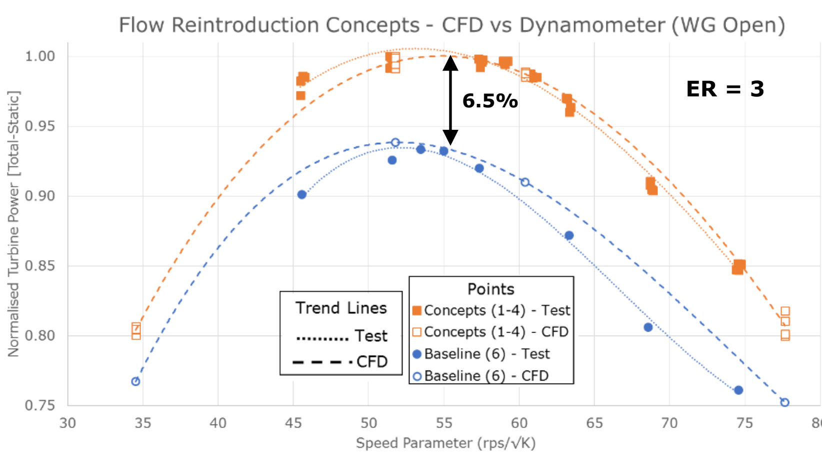


Figure 4.3 – Flow reintroduction port design wastegate open results

It can be seen from Figure 4.3 that there is a large increase in the turbine power produced by all of the concepts in comparison to the baseline. As in the previous sections, the improvement over the baseline is due to a decrease in the static pressure at the wheel outlet. This is due to both a reduction in the wastegate mixing loss (4%) and the pressure recovery from the turbine diffuser (2.5%). This breakdown is inferred from the wastegate-closed efficiency improvement.

This plot also shows that the turbine stage efficiency is insensitive to the exact design of the flow reintroduction port. Each design is significantly different and yet each is efficiency transparent. This is a useful learning, it shows that the flow reintroduction angle is the greatest lever and that the method of reintroduction can be optimised for manufacturability.

5 STUDY III - WASTEGATE BYPASS CAPABILITY

The final study aims to identify a relationship between the aerodynamic area of the flow reintroduction ports and the bypass capability of the turbine stage for a fixed diameter wastegate port. This is a critical parameter in wastegated turbochargers because if there is a restriction to the bypass capability then at rated engine conditions the turbocharger will over-speed. This will be accentuated further by higher performance turbine stages due to an increased requirement for flow bypass as discussed in Section 1 and 4. Thus any optimum flow reintroduction method must ensure that it causes no restriction to bypass capability.

Study II showed that wastegate mixing losses were insensitive to reintroduction port design, thus for ease of manufacture, concept 1 was selected for this study (boreholes). This method varies the aerodynamic area of the flow reintroduction port by changing the diameter of the boreholes on the connection adapter.

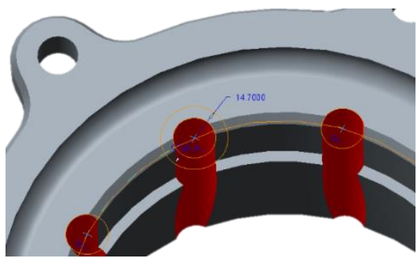


Figure 5.1 – Flow reintroduction area port variation method

As in Study II, both CFD and test data were utilised. This again allows us to validate the CFD result.

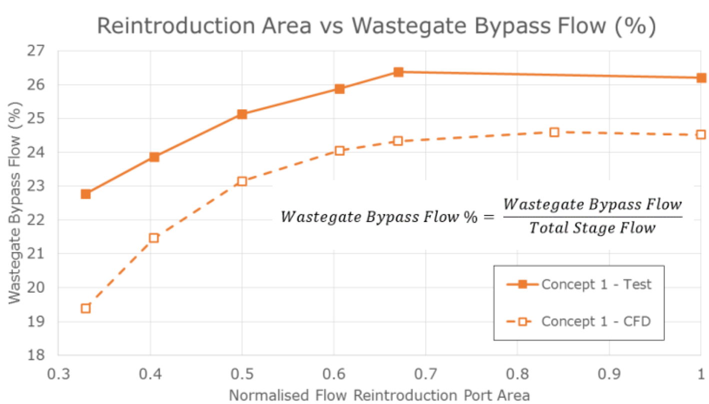


Figure 5.2 – Wastegate bypass capability for varying reintroduction area

Although the exact numerical figures for bypass capability vary between CFD and test the trend remains the same. This trend shows that the bypass capability of the turbocharger is restricted by the flow reintroduction port until it reaches a normalised area of around 0.7. After this area, the bottleneck to the bypass flow becomes the wastegate port. In order to bypass more the area of the port needs to be increased.

6 CONCLUSION

It was the aim of this paper to both identify and characterise the key parameters which govern the wastegate mixing losses evident in current product wastegate housings in an effort to increase turbine stage efficiency. By observing the fluid interactions as the bypass flow is reintroduced into the bulk flow, it is clear that there is a significant disruption. This breaks down into one main theme, an increased back pressure at the turbine wheel outlet. Thus the wastegate-open turbine stage efficiency is reduced through a decrease in the available energy.

The subsequent studies within this paper identified several key learnings which when combined generated a 6.5% increase in turbine power in wastegate-open condition compared to the baseline turbine stage. The first and most important discovery was the effect that flow reintroduction angle has on the back pressure at the wheel outlet. The more collinear the bypass flow the lower the static pressure at the wheel and the higher the wastegate-open turbine stage efficiency. The second study identified that the stage efficiency was insensitive to flow reintroduction port design. This allows for more robust, less performance-driven designs to be used with little penalty. Finally, the last study highlighted the importance of understanding the relationship between bypass capability and flow reintroduction port area. If a design does not take this into considerations it can cause significant restrictions and lead to over-speeding.

In summary, today’s turbocharger market is constantly driving for higher efficiency and reduced emissions. CTT has developed guidelines for the deployment of more optimum wastegate configurations in current product which will lead to more efficient turbocharged engines.

7 REFERENCES

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