

Combined WAVE-VECTIS simulation of an intake manifold of V6 PFI gasoline engine

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Abstract

This paper describes the analysis of the flow in the intake manifold of a V6 gasoline engine performed using WAVE 1D engine cycle simulation program alone first, and then using WAVE coupled with 3D CFD VECTIS. The work shows how modeling in 3D selected components of the inlet manifold embedded within the 1D flow network leads to improvements in prediction accuracy.

Introduction

The main purpose of this work was to improve the WAVE model of the V6 3.2l engine, scheduled for installation in the GTA version of the popular Alfa Romeo 156 vehicle. Moreover, this work was also part of a comparative study between two intake manifolds differing in shape and volume.

Whilst the performance of an engine is typically investigated using the 1D engine cycle simulation program WAVE alone, for this application the authors believe that only the use of the 3D CFD code VECTIS coupled with WAVE can accurately capture how the manifold influences the behaviour of the engine.



Fig. 1: Alfa Romeo 156 vehicle

The WAVE model of this engine was derived from the V6 3.0l engine model which powers the Alfa Romeo 166 vehicle.

The use of the 3D mesh has been limited to specific components of the intake system that are likely to generate a very complex, 3D flow. This allows to minimize the unavoidable increase in runtime associated with CFD.

The calculation provided interesting engine performance results (such as overall and individual cylinder volumetric efficiency, mass flow rate and power) when compared with the WAVE simulation alone, and very useful insights into the 3D flow patterns inside the intake system.

WAVE model of V6 engine

WAVE is an engine performance and gas dynamic simulation software, developed by Ricardo, that enables simulations to be carried out on virtually any intake, combustion and exhaust system design.

VECTIS is a general-purpose Computational Fluid Dynamics program developed specifically to solve complex flow problems found in Internal Combustion Engines and Vehicles.

Ricardo Software has created the possibility to couple the two codes at time step level: the user can insert one or multiple 3D VECTIS flow domain/s inside the WAVE network. The coupling methodology allows VECTIS to be started automatically as a child process of WAVE after WAVE itself has reached a convergence on a 1D-only flow network including what is called a "shadow" network, i.e. that part of the model that will be replaced by the 3D CFD flow domain.

In this case, the intake manifold connecting the throttle body to the 6 runners was represented in WAVE with a number of Y-junctions and of zero-length ducts, and was connected to the rest of the 1D network using seven 1/8 junction. These represent the interface boundaries between the 1D and the 3D computational meshes.

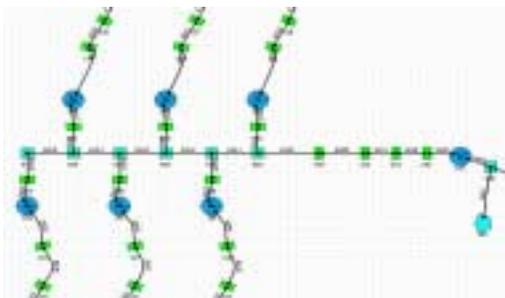


Fig. 2: WAVE "shadow" model of intake manifold with the 1/8 y-junctions

While the leading code is WAVE, the timestep is actually imposed by VECTIS. WAVE provides VECTIS with information on mass flow rate, average density, pressure and temperature calculated at every step through the interfaces. VECTIS, after performing the calculation during the timestep, gives back to WAVE the updated data averaged over the boundary regions.

The connection between the two codes was accomplished using the VECTIS-specific 1/8 junctions, which have been since replaced by the more general 1/10 junctions. The type of junction chosen does not affect the final output of the calculation.

VECTIS model of intake system

The VECTIS model has been created starting from a 3D CAD assembly.

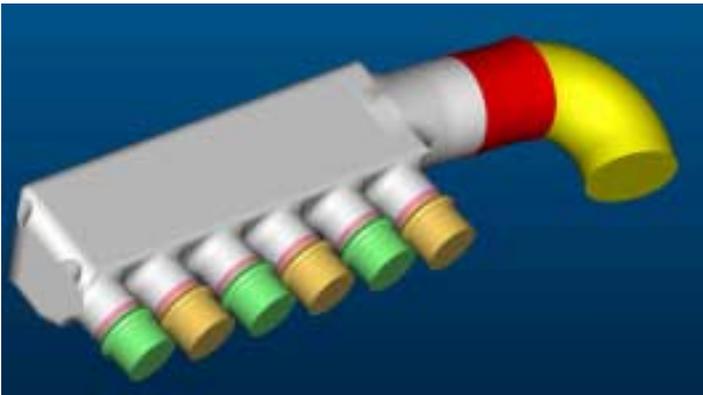


Fig. 3: Cad assembly of intake manifold

The different components of the VECTIS model are:

- the duct from the last bend of the intake system to the throttle body (Fig. yellow)
- the throttle body itself (Fig. red)
- the internal surface of the intake manifold (Fig. grey)
- the straight part of the runners (orange/green for the two banks of engine)

The mesh used is made of 10 mm cubic cells, with local refinements of level 2,1 extended on the volume of the intake manifold and, if present, of level 2,2 around the throttle.

A transversal section of the mesh is presented in the following figure 4.

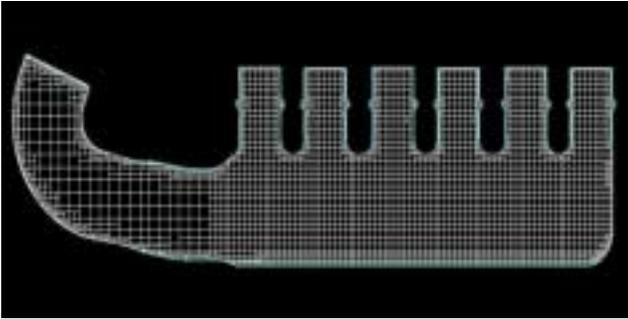


Fig. 4 : Section of VECTIS meshed calculation

Summary of performed calculations

The following calculations have been performed:

1. Comparison of WAVE/VECTIS simulations with and without 3D model of throttle, at 6000 RPM
2. WAVE/VECTIS simulations at 6500 RPM without throttle
3. WAVE simulation throughout the power curve in comparison with experimental results
4. Optimization of WAVE model at the simulated engine speeds

The two first WAVE-VECTIS combined simulations, performed at 6000 RPM, wanted to clarify the importance of modelling throttle on the performance output of the engine and to test the sensibility of 3D code at such a change in geometry.

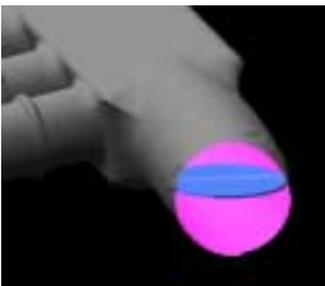


Fig. 5: detail of VECTIS domain with throttle

It is reasonable to expect a small effect on performance, which would allow to avoid meshing the throttle.

The difference in mesh size and, consequently, on the computational time, between the two models is about 30,000 cells.

For every simulations the estimated roughness of the throttle is 0.1 mm, whilst that of the internal surface is 0.2 mm.

Leaving the same WAVE network, the differences of performance between the two models are shown in the following figure.

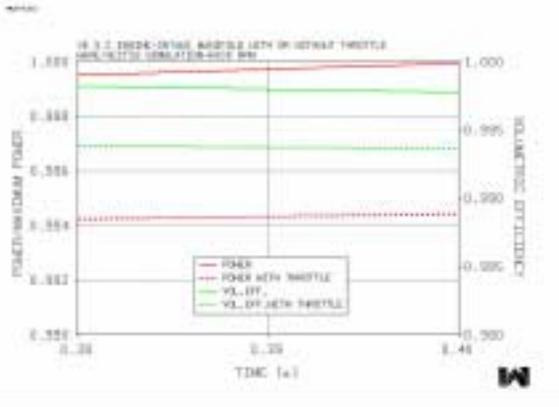


Fig. 6: effect of simulating throttle

Every result is normalized with reference to the maximum estimated power of the engine. The results show that it is not necessary to mesh the throttle as the difference of the predicted power is less than 0.6 %.

Focusing now our attention on the calculation at 6000 RPM without throttle, some differences occur between the results given by the WAVE and by the WAVE/VECTIS runs.

These differences are shown in the following figures:

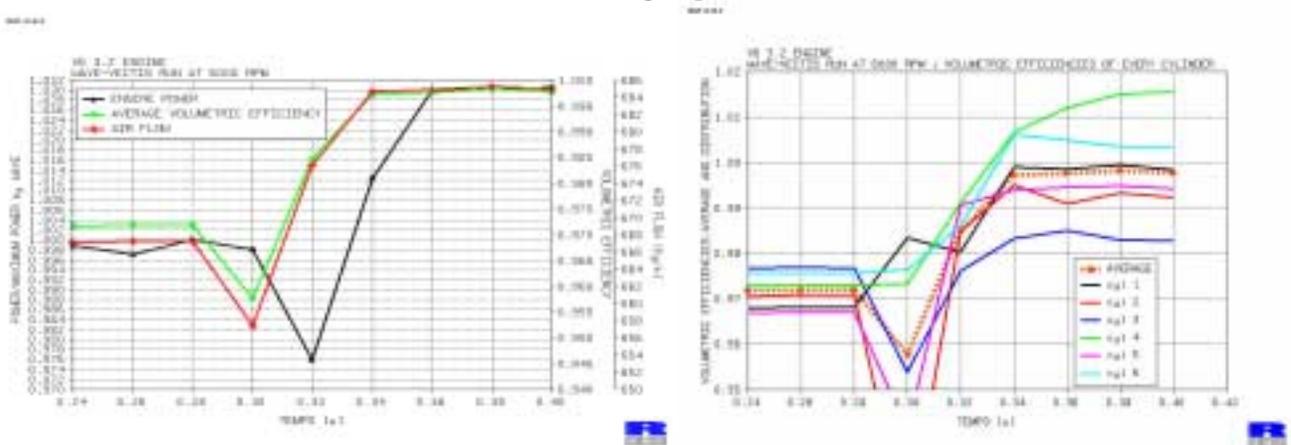


Fig. 7: engine performance at 6000 RPM

The results shown in these output plots are from WAVE-only up to 0.28 s, and from the combined WAVE/VECTIS after that.

The combined WAVE/VECTIS simulation shows an increase of approx. 3% in the estimated maximum power, as well as in air flow and volumetric efficiency. There is also a significant difference in the values of volumetric efficiency in the 6 cylinders, as well as for the ranking among them.

Indeed, the most efficient cylinder in the WAVE run (#3, which is the closest to the throttle body), is the worst in the WAVE/VECTIS one. Moreover, cylinder #4, which is the farthest from the throttle, is by far the most efficient in the WAVE/VECTIS simulation.

As VECTIS models the real geometry of the manifold and solves the physical equations at a more fundamental level, the results and directions of the WAVE/VECTIS predictions will be used to fine-tune the WAVE-only model. It must be remembered that a WAVE/VECTIS calculation is only a special case of WAVE simulation. Naturally, every other parameter (spark advance, a/f ratio, wall temperatures, etc.) has not been changed between the two cases.

Two hypothesis have been formulated to justify these differences and to modify consequently the WAVE model:

- 1) underestimation of losses, (friction/inlet losses), and/or heat transfer coefficient used in the WAVE model
- 2) different tuning of the engine, seen from the two codes

In order to understand the different behaviour inside the manifold, the following monitoring points have been placed in the VECTIS 3D mesh and in the equivalent WAVE 1D mesh:

- beginning of elbow along the intake duct
- inlet of the throttle body
- outlet of the throttle body
- inlet of main volume of intake manifold
- centers of every subvolume which compose the manifold
- at 40 mm from the edge of the main volume, along every runner

The locations of these monitoring points are shown in green in the following figures:

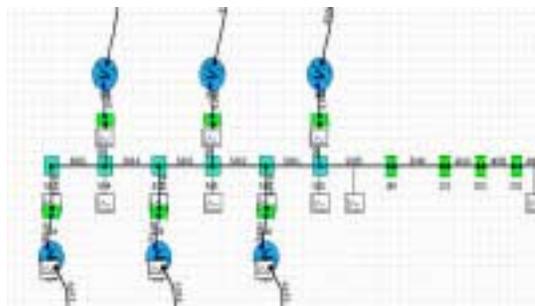
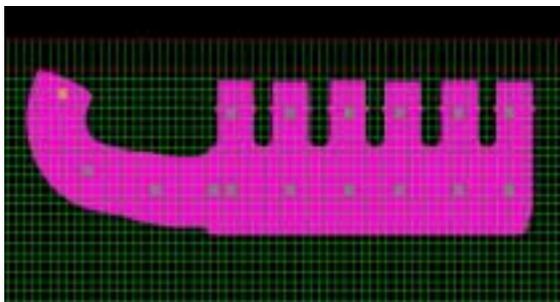


Fig. 8/9: Monitoring points in WAVE and VECTIS model

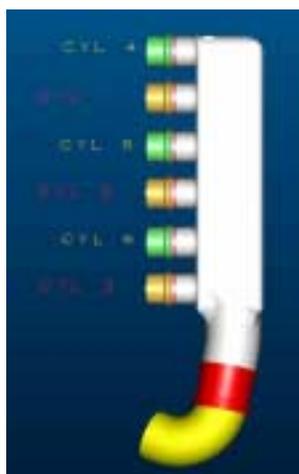


Fig 10: Cylinder numbering

We can compare the WAVE and the WAVE-VECTIS results of predicted pressure and temperature in the same points.

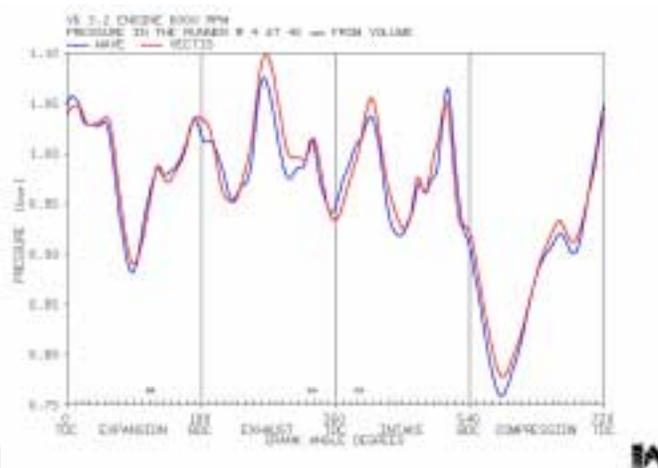
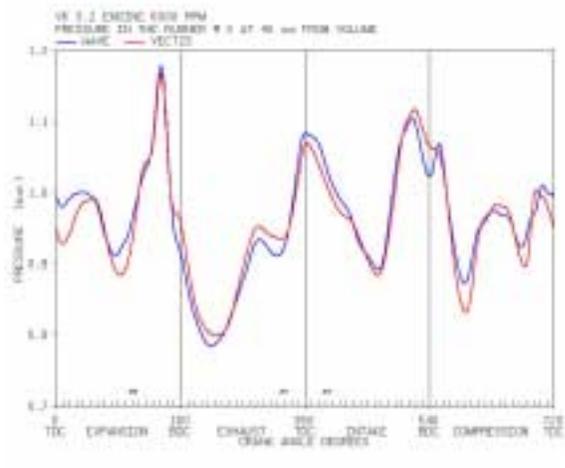


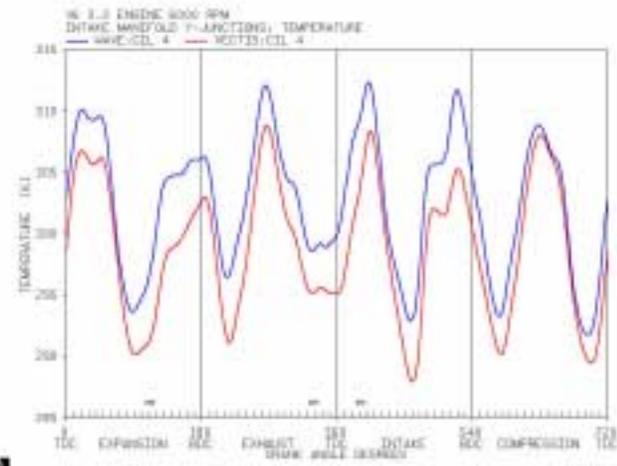
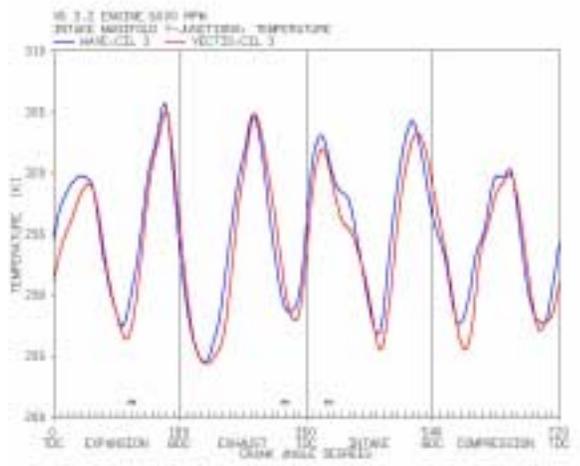
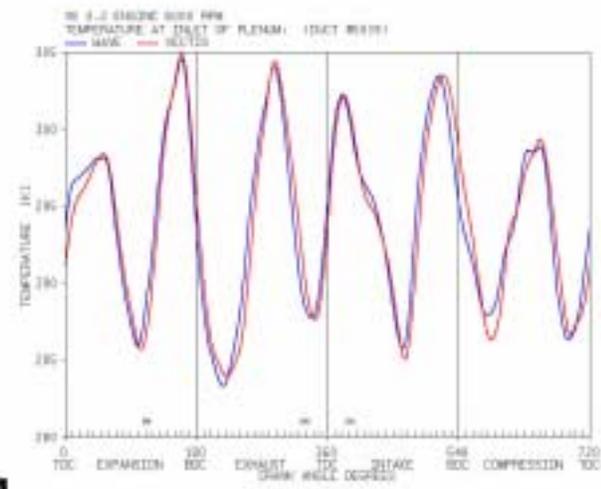
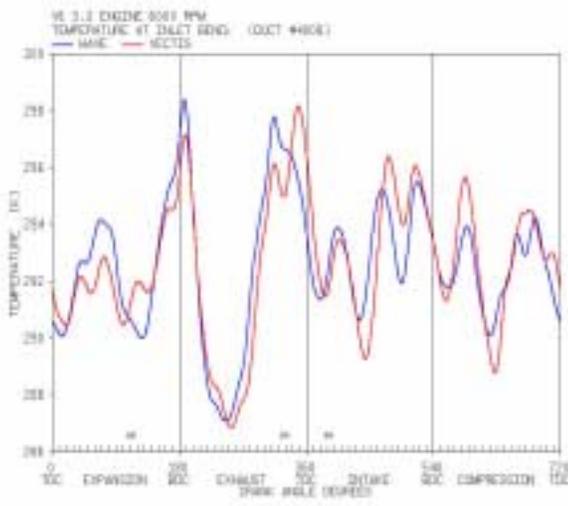
Fig. 11: WAVE and VECTIS predictions of pressure in the runner of cylinders #3 and #4

As the previous figures show, there are no significant differences between the pressure traces predicted by WAVE and by WAVE/VECTIS.

The figures refer to the pressure calculated in the runners, which are very close to the WAVE/VECTIS boundaries, and consequently the most significant.

We are then able to conclude that pressure losses are generally accurately modeled in WAVE, the only slight difference occurring during the intake phase of every cylinder, where the VECTIS prediction is higher than the WAVE one.

This can explain in part the better volumetric efficiency estimated by VECTIS.



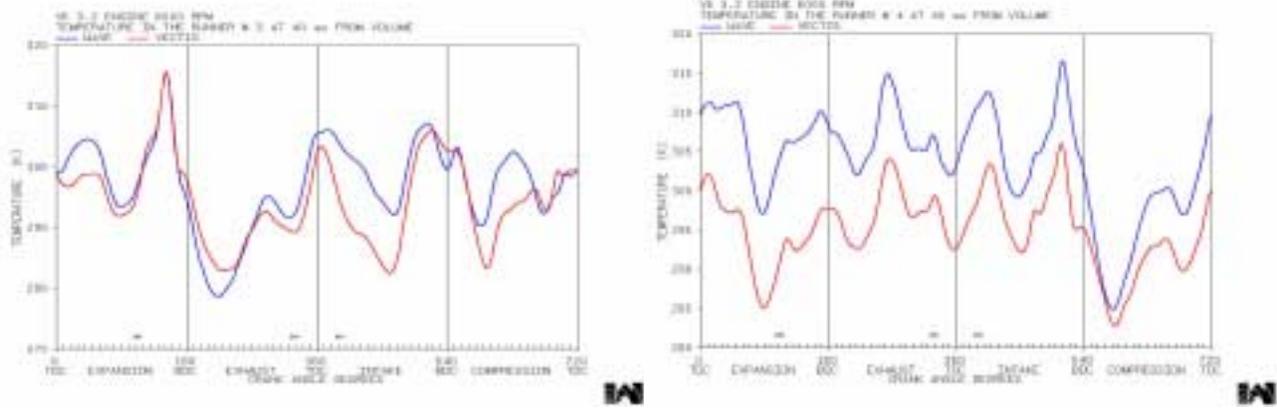


Fig 12: compared WAVE and WAVE/VECTIS predicted air temperature in several monitoring locations

On the other hand, the previous graphs show a significant differences between the predicted temperatures from the two cases. Therefore, we can conclude that the better overall volumetric efficiency and the different ranking between the 6 cylinders showed by the WAVE/VECTIS are mainly due to the different behaviour of the two codes regarding heat transfer between the air and the manifold walls.

In the WAVE/VECTIS simulation, the further the point is from the intake duct, the lower is the increase in air temperature in comparison with WAVE-only.

The two predictions are very similar along the duct responsible for bringing the air to the plenum, but they begin to show appreciable differences in the main plenum, modeled with a series of y-junctions in WAVE.

As a result, the gap between WAVE and WAVE/VECTIS predicted performances is very significant for the runner #4, which is opposite to the throttle, and also for #3.

The conclusion is that the estimated heat transfer from the walls to the air is higher in WAVE than in VECTIS.

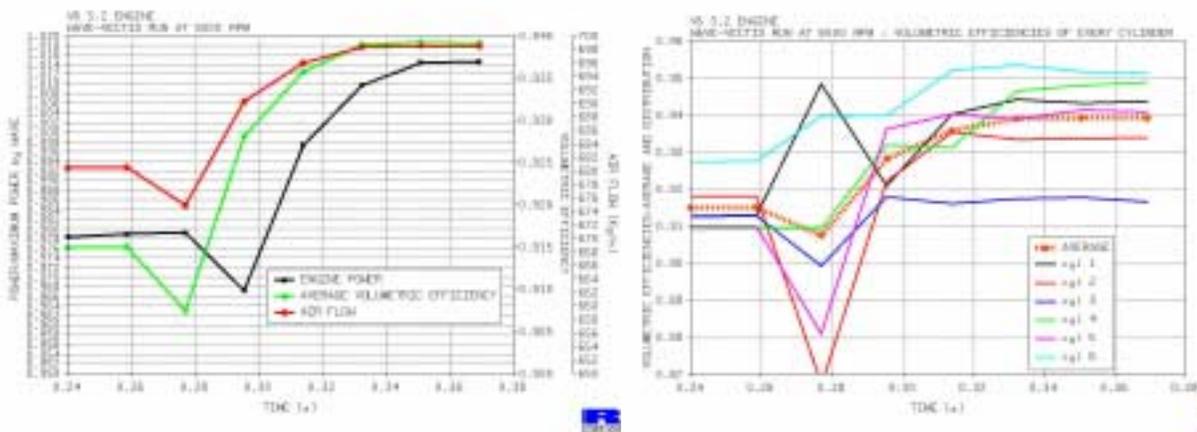


Fig. 13: differences in engine performance at 6500 RPM

While the behaviour of engine performance and volumetric efficiency for this case is very similar to the 6000 RPM one - see Fig. 13, the ranking of volumetric efficiencies is quite different.

This could depend on the flow field due to the different engine speed and can be investigated further by looking at the VECTIS POSTprocessing file.

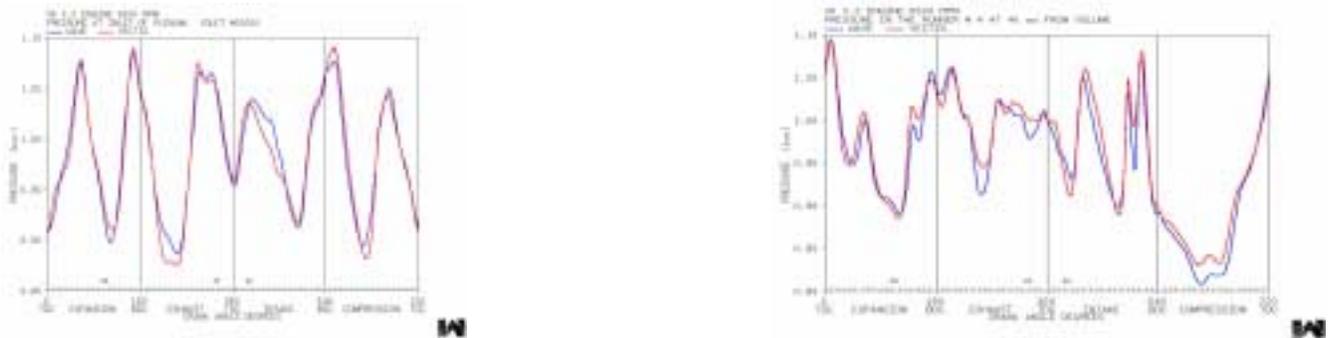


Fig. 14: pressure predictions at 6500 RPM

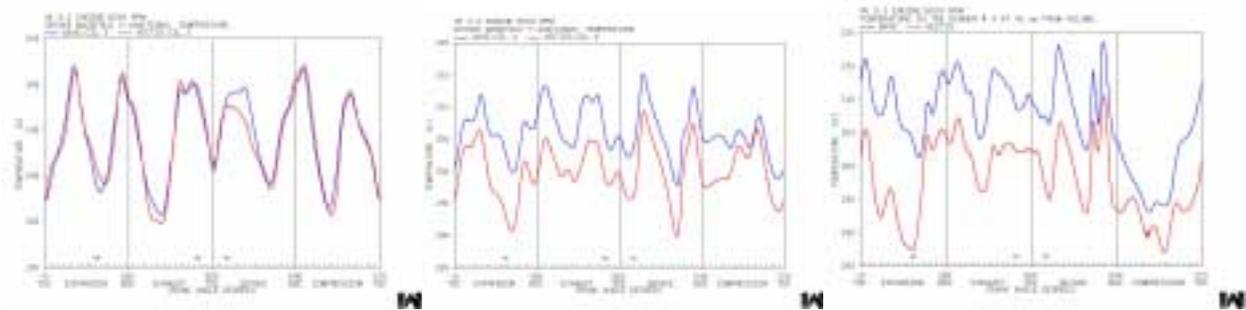


Fig. 15: temperature predictions at 6500 RPM

Regarding temperatures similar conclusions can be drawn here also.

One reason for this difference for cylinder #4 could be that it exchanges heat not only with the lateral wall, as all the other ones, but also with the wall opposite to the throttle.

As WAVE overestimates the heat transfer from the walls to the air, this can bring to a strong increase in temperature.

Optimization of intake manifold WAVE model by using WAVE/VECTIS results

There are different parameters to be modified in order to optimize the WAVE model of the intake manifold and obtain a better agreement with experimental results.

Basically these parameters are:

DIAB = geometric parameter =diameter of every y-junctions of manifold seen from the runner

CHT = multiplier coefficient of heat transfer, referred to intake ducts and y-junctions which compose the intake manifold

CD = coefficient to take in account the pressure loss associated with an abrupt change of area (in this case is from the y-junction of the manifold to the circular 43 mm internal area of the runner)

The initial values of these three parameters were:

DIAB = 70 CHT = 1 CD = 0.96

When the WAVE model of the intake manifold is created, the DIAB is estimated from geometric dimensions of the sub-volume which is to be represented with a y-junction.

Since estimating the acoustic effect of a duct connected to a volume can be difficult, it is not always easy to find the right value for DIAB to be used in the WAVE model.

The same considerations apply to the CHT coefficients as well as for the CD parameter.

As the figure 16 shows, there is a strong dependance of engine power on DIAB.

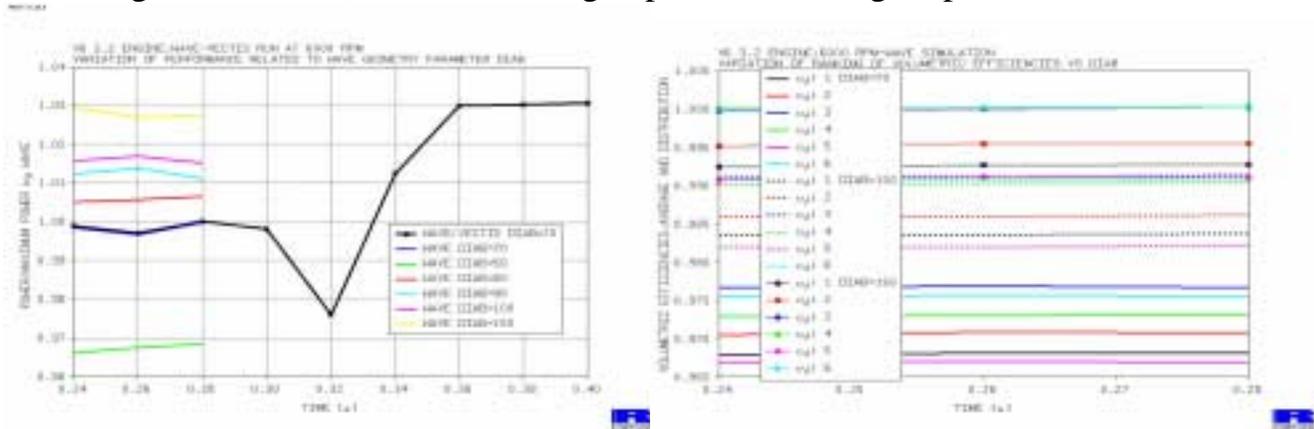


Fig. 16: relationship between performance and parameter DIAB (6000 RPM)

It would seem that the DIAB parameter affects much more the overall value of volumetric efficiency than the ranking among the the cylinders.

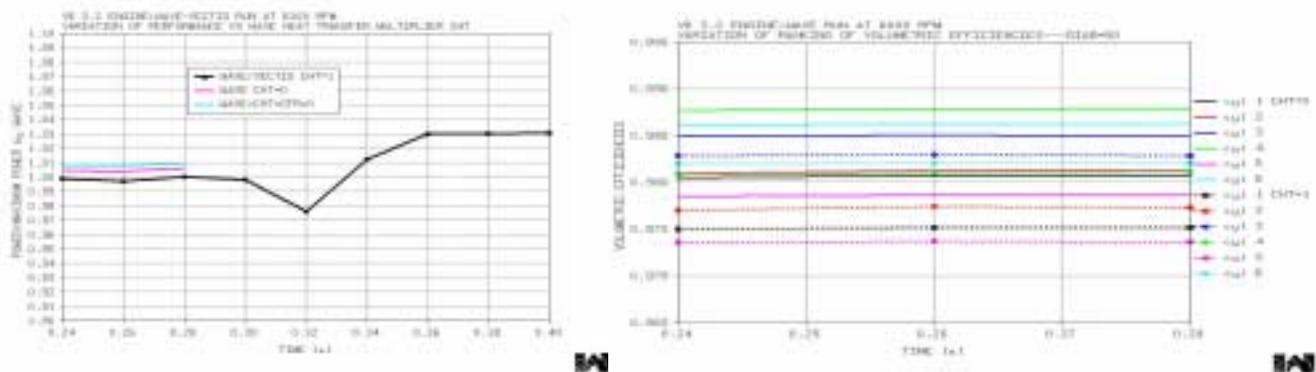


Fig. 17: relationship between performance and parameter CHT (6000 RPM)

On the other hand, the CHT parameter seems to affect the ranking of the volumetric efficiency of individual cylinders.

As an extreme case, setting CHT to 0 for the whole intake manifold causes the volumetric efficiency of the 4th cylinder to become the highest, and the overall volumetric efficiency to increase also, similarly to the WAVE/VECTIS run shown in Fig. 17. Moreover, the pressure calculation in the 4th y-junction shows that there is a much better agreement with VECTIS prediction if the WAVE run is performed with CHT=0 (Fig. 18).

Similar conclusions can be drawn for the 6500 RPM case.

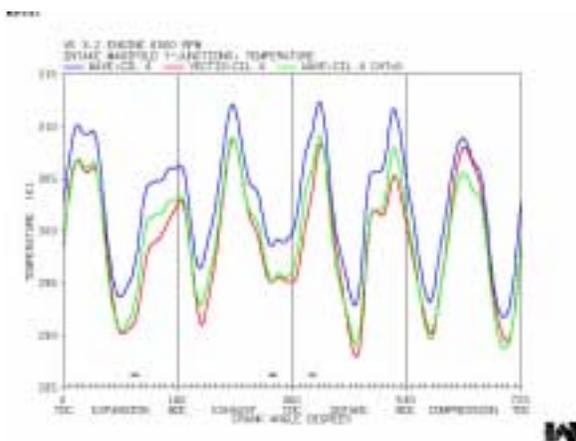


Fig. 18: influence of CHT on WAVE prediction

Now we can fine tune the WAVE model by adjusting the parameters identified in the previous section in order to match the engine performance results obtained with WAVE/VECTIS combined.

This process lead to the following values:

DIAB = 100

CHT = 0.1

CD = 0.98

The result is showed in the next image:

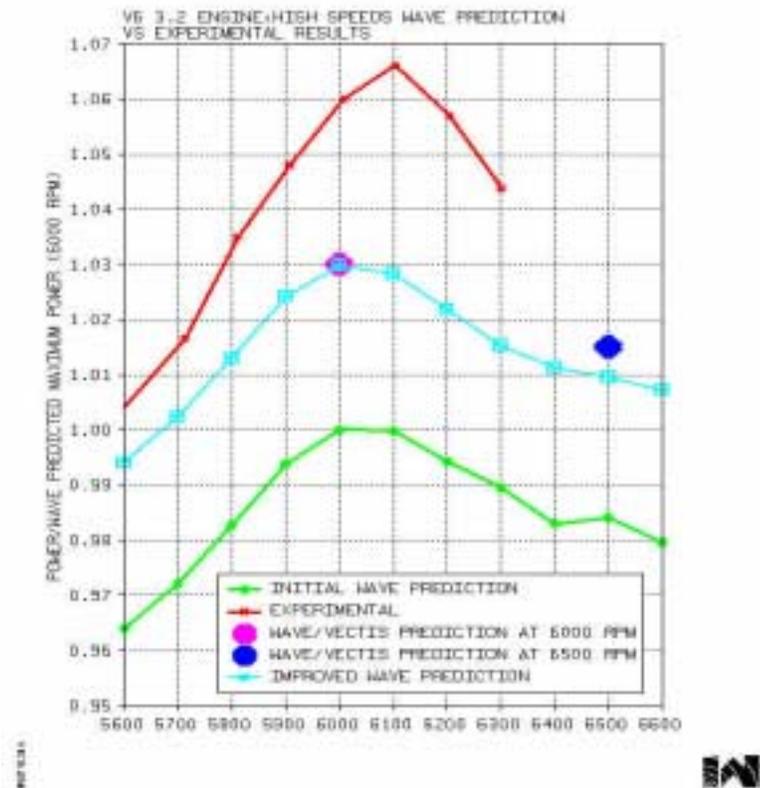


Fig. 19: improvement of WAVE prediction through WAVE/VECTIS optimization.

With this improved WAVE model based on the WAVE/VECTIS results and considerations, the difference between experimental results and WAVE prediction has been reduced.

Clearly, other aspects of the WAVE model must be improved further in order to minimize the gap.

An experimental test has been done to validate the calculation results.

Some pressure sensors have been positioned approximately in the same locations as the monitoring points. The exact spacial correspondance was not possible, as there were

physical limitations in the actual placement of the pressure sensors so that the measurements were reliable. This must be remembered when comparing the results.

These experimental curves are to be considered as an indication of the average good agreement of calculation with test bench, but unfortunately not as a confirmation of conclusions done on WAVE/VECTIS behaviour versus WAVE-only.

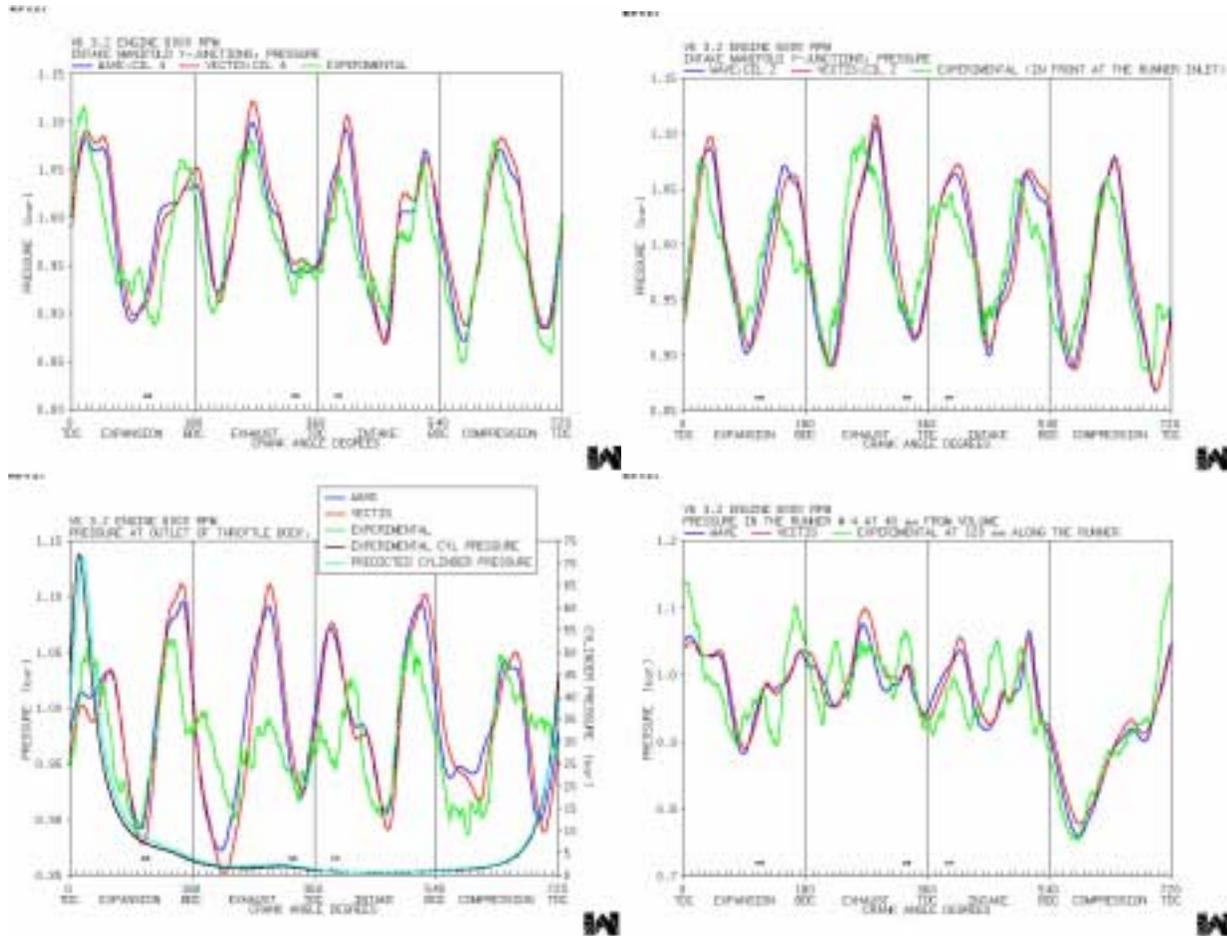


Fig. 20: WAVE and WAVE/VECTIS predictions and experimental results.

There is a generally good agreement between prediction and experience, except for the throttle outlet, the throttle being clearly a very difficult flow element to capture and one that creates a very perturbed and potentially varying flow downstream.

Computational times

The computational times are summarized in the following table:

Calculation	Mesh size	WAVE/VECTIS computational time
6000	60000	140 h = 5.8 days
6000 throttle	90000	170 h = 7.1 days
6500	60000	140 h = 5.8 days

Pre-processing work can be estimated in around 7/8 hours, starting from CAD model. Every calculation has been performed on a single-processor SUN workstation with 384 Mbytes of RAM and 360 MHz speed.

A very significant reduction in run-time can be achieved with a parallel calculation on a multi-processor workstation.

Conclusions

The WAVE/VECTIS calculation enables us to improve the WAVE model of V6 3.2l engine and to better know what is the real behaviour internally to the intake manifold. As VECTIS models the real geometry of the manifold, meshed with a much finer mesh than WAVE, and solves the physical equations at a more fundamental level, there are no doubts about the greater accuracy of the WAVE/VECTIS prediction in comparison with WAVE-only.

Several conclusions can be summarized:

1. It is not necessary to mesh intake ducts in 3D CFD since WAVE and WAVE/VECTIS predictions are similar along those elements
2. VECTIS run provides us with indications on choice of important WAVE parameters
3. The internal behaviour of air into the manifold can be investigated through the analysis of VECTIS POSTprocessing file.
4. A coarser CFD mesh is to be investigated in order to decrease long computational times