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EXECUTIVE SUMMARY OF THE THESIS

1-D Fluid Dynamic Modelling and Analysis of Pipe Junctions in IC Engines

TESI MAGISTRALE IN ENERGY ENGINEERING – INGEGNERIA ENERGETICA

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1. Introduction

The fluid flow in the manifolds of internal combustion engine is a complex phenomenon. The complexity arises due to the cyclic process of replacement of charge in the engine cylinders, multidimensional flows, uneven geometries, and unsteady processes. Countless methods and technologies have been adopted for the evolution of internal combustion engines.

In early stages the experimental methods were the basis of research. Obviously, these methods were expensive, time consuming and several limitations were associated with them. In the middle of 20th century, numerical methods were developed which relies on computational fluid dynamics to predict the wave propagation in the engine manifolds which directly effects the engine performance. These numerical methods have also been in continuous development phase and vary depending on the hypothesis adopted, computational times, accuracy, and methodology. These methods provide a basis for predicting the engine behavior at design stages and can simulate the engine operation cycles. The use of these numerical models allows to minimize the experimental procedures adopted and thereby reducing the associated costs.

Majority of the simulation codes are based on the one-dimensional system of governing equations instead of the three-dimensional approach, this is due to the short computational times provided by the one-dimensional system. Although the accuracy of the results is compromised but a good balance between accuracy and computational speed is maintained by preferring the one-dimensional system over the three-dimensional system. Convergence is achieved after computation of multiple cycle thus one-dimensional approach is used by most of the simulation tools.

The inclusion of geometrical conditions and effects of directionality of flow which are complex is possible by incorporation of boundary conditions at the junctions in the one-dimensional approach. Different models have been developed for various boundary conditions at junctions are discussed in the thesis. These models include the constant pressure junction models and pressure loss junction models.

The simulation tool Gasdyn which was developed in Polimi, also relies on the one-dimensional approach for the engine simulation. Gasdyn utilizes multiple computational codes for the solution of different junction types. These computational codes are referred to as subroutines in this thesis work. Several junction types and their associated models and subroutines are discussed and analyzed.

As the main objective of this thesis work, a new general subroutine is developed which is more accurate, robust and can be applied in general to all the constant pressure-based junction types. The results obtained from this new subroutine are validated by substituting the old subroutines individually in the main program code for the engine simulation and compared with those obtained by the old subroutines for different engine configurations. After individual substitution validation, the simultaneous substitution is performed for all old subroutines based on the constant pressure junction models. The results obtained after the development of the new subroutine demonstrated that the new routine performs accurately and has replaced the previously utilized subroutines for junction of n-pipes, catalysts, intercooler and perforates in the main Gasdyn program code.

2. Fundamental equations

The analysis of fluid flow in the manifolds of the internal combustion engine is associated with the pressure waves which propagates through a system of pipes and junctions. To reduce the complexity of the system of equations, following hypothesis is adopted for the flow through the ducts [1]

- Viscosity of the fluids is neglected
- Fluid dynamic properties are a function of space and time

$$f = f(x,t)$$

- The flow is one-dimensional, and the fluid dynamic properties are identical for a given cross section
- Heat exchange at the walls of duct
- Fluid is compressible
- Non isentropic processes
- Friction between the fluid and walls of the duct are considered

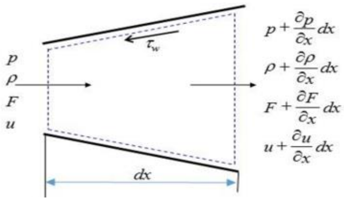

Figure 1: Control Volume for a Mono-dimensional Scheme for 1-D analysis

Based on these hypotheses, the conservation equations for mass, momentum, and energy along with the ideal gas equation of state are written for a duct with variable cross-sectional area as below.

$$\begin{cases} \frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial t} + \frac{\rho u}{F} . \frac{dF}{dx} = 0 \\ \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \frac{1}{\rho} \cdot \frac{\partial p}{\partial x} + G = 0 \\ \frac{\partial\left(\rho e_o F\right)}{\partial t} + \frac{\partial\left(\rho u h_o\right)}{\partial x} - \rho \dot{q} F = 0 \\ P = \rho R T \end{cases}$$

The necessity to include the ideal gas assumption hypothesis derives from the fact that the system of equation has four unknowns being the fluid velocity, pressure, density, and internal energy.

3. Numerical Methods

The system of equation described in the previous section are written in vector form as below:

$$\frac{\partial W(x,t)}{\partial t} + \frac{\partial F(W)}{\partial x} + B(x,W) + C(x,W) = 0$$

Where W is a vector of conserved variables, F being the vector of fluxes, B & C are the vector of source terms including frictional forces, pressure forces and heat exchange. The vectors written in matrix form are.

$$W(x,t) = \begin{bmatrix} \rho F \\ \rho u F \\ \rho e_0 F \end{bmatrix}$$

$$F(W) = \begin{bmatrix} \rho u F \\ (\rho u^2 + p)F \\ (\rho e_0 u + up)F \end{bmatrix}$$

$$B(x, W) = \begin{bmatrix} 0 \\ -p\frac{\partial F}{\partial x} \\ 0 \end{bmatrix}$$

$$C(x, W) = \begin{bmatrix} 0 \\ -\rho G F \\ -\rho \dot{q} F \end{bmatrix}$$

The governing equations are solved by different techniques proposed by various authors. The first method that was adopted for this purpose was the Method of Characteristics (MOC) proposed by Riemann [2]. This method uses traceable line called characteristic lines along the field of flow and transforms the partial differential equations into ordinary differential equations along these characteristic lines. This method is simple but provides first order accuracy in time and space. Other methods which are more accurate were developed. These include the Shock Capturing techniques which provide second order accuracy and able to capture the discontinuities in the field of flow. But these are also accompanied with spurious oscillations specially around the shock waves. In order to avoid spurious oscillations a method was proposed by Corberan known as Corberan-Gascon TVD (Total Variation Diminishing) scheme. These methods are discussed in detail in the thesis. [3]

4. Dimensionless Variables

If the pipe mesh stencil in time and space domain is represented by the *Figure 2* which is adopted as the basis for the numerical methods.

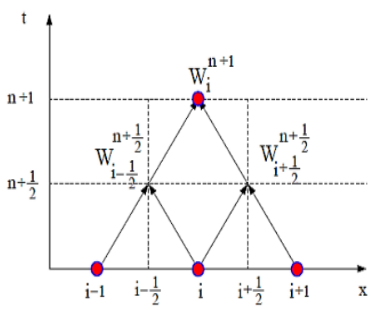

Figure 2: Mesh stencil in space and time domain

To find the pipe conditions at time interval n+1, for any point node i, the information of the pipe conditions at the adjacent nodes i+1, i-1 is required at the previous time interval n.

The Riemann invariant for homentropic flow defined as

$$\lambda = a \pm \frac{k-1}{2} u$$

Since the flow in manifolds are affected by heat exchange at the duct walls and friction between the flowing fluid and duct, the entropy level does not remain constant, and the Riemann invariant defined above does not remain constant and referred to as the Riemann variables. The superscript * is used to denote the variables defined for non-homentropic flows. [2]

The dimensionless variables are used throughout the solution procedure.

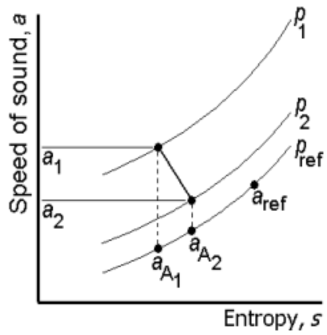

Figure 3: Reference sound speed and entropy diagram

$$A = \frac{a}{a_{ref}}; \quad U = \frac{u}{a_{ref}};$$

$$\lambda = A \pm \frac{k-1}{2} U$$

For the non-homentropic flow the dimensionless parameters are redefined in starred variables

$$A^* = \frac{A}{A_A}; \quad U^* = \frac{U}{A_A};$$

$$\lambda * = A^* \pm \frac{k-1}{2} U^*$$

5. Junction models

The one-dimensional hypothesis for three dimensional flows in the parts of the ducts specially the junctions is a simplification procedure that is adopted, but at certain points this hypothesis is an oversimplification that could result in inaccuracies. Boundary conditions are adopted to compensate the directionality of flow induced by the junction. The boundary models adopted for this purpose can be distinguished into two types:

- Constant pressure junction model
- Pressure loss models

5.1 Constant pressure junction model

The constant pressure model is based on the hypothesis proposed by Benson [1], assuming equal static pressure for each duct connected to the junction. Mathematically

$$p_1 = p_2 = p_3 = \ldots\ldots = p_n$$

This is a simple model for the solution of junction, it does not require any loss data, and neglects the angle between the branches

Benson defined the procedure for evaluating entropy levels at the ends of duct connected to the junction as:

- For the pipe ends where the flow is positive or towards the junction ($U^*_N > 0$), the entropy levels remain unchanged and (AA_N) is equal to the previous value of AA_N
- For the pipe ends where the flow is negative or towards the junction ($U_N^* < 0$), the entropy levels remain does not remain the same and is calculated as the weighted average of the entropy levels of the joining flows.

We can summarize the above points proposed by Benson as:

$$U_N^* = \frac{2}{k-1}(\lambda^*_{\mathrm{inN}} - A_N^*)$$

$$\begin{cases} If\ U_N^* > 0\ ;\ AA_N = AA_N \\ If\ U_N^* < 0\ ;\ AA_{N\,(N=NS)} = \dfrac{\sum(U_N F_N A^*_{AN})}{\sum(U_N F_N)} \end{cases}$$

Thus, due to the variation of entropy level, the Riemann variables are updated,

$$\lambda^*_{\mathrm{inNc}} = \lambda^*_{\mathrm{inNn}} + \frac{A_N}{A_{A_{N_C}}}(A_{A_{N_C}} - A_{A_{N_n}})$$

Where the subscript Nc represents the corrected or updated value of the Riemann variables, and the subscript Nn represents the respective initial values.

The final Riemann variable is then calculated:

$$\lambda_{\mathrm{outN}} = A_{A_{N_c}}(2\,A^*_{\mathrm{N}} - \lambda^*_{\mathrm{inNc}})$$

The procedure is adopted iteratively until the solution reaches a convergence such that the two successive values of A^*_N are within a tolerance limit difference.

The constant pressure model is applied when the variation of the cross-sectional area and mass flow rate and angle between the ducts is not high. This model is a good approximation for most junction types used in the engine manifolds. The computational codes for the solution of junctions including catalysts, intercooler, perforates and junction of n-pipes are based on the theoretical constant pressure model [1]

5.2 Pressure Loss models

Unlike the constant pressure model, the pressure loss models consider the pressure drop across the junction. Variants of pressure loss models are proposed by different authors. The pressure loss models include the effects of directionality of flow.

A pressure loss model for three duct junctions was proposed by Benson, which relies on the steady flow pressure loss coefficients. A theoretical model is also presented in the thesis which can calculate the pressure loss coefficients based on the type of flow as separating or joining for junction configurations involving three ducts.

A model was proposed by Bingham & Blair [4] that requires the junction to be classified as separator or collector before proceeding to the junction solution was presented. Bingham also generalized the expression & related the pressure drop across the junction to the angular relationship between the branches and denotes the loss coefficient as:

$$C_j = 1.6 - \theta_d \frac{1.6}{167}$$

This model by Bingham & Blair was found to give inaccurate prediction in case of high mass flow ratios and cross-sectional area variation among the considered ducts.

Winterbone & Bassett [5] proposed a model for the prediction of pressure drop across the junction with multiple ducts connected, where the pressure drop among the datum branch and the considered branch was a function of the angle between the branches (θ) along with the mass flow (q) ratio and cross-sectional area ratio ψ. The datum branch was defined as the branch with the greatest mass flow in the positive direction (towards the junction). The loss coefficient is given as:

$$C_j = 1 - \frac{1}{q_j \psi_j} cos\left[\frac{3}{4}(\pi - \theta)\right]$$

This model is more robust and accurate than the other models proposed and does not rely on experimental steady flow data, moreover this model can be applied to any junction without limit to the number of ducts [5]

A comparison of the loss coefficients as predicted by the Bingham & Blair's model with the Winterbone's model is represented in the *Figure 4*, where the loss coefficient is plotted against the angle between the branches.

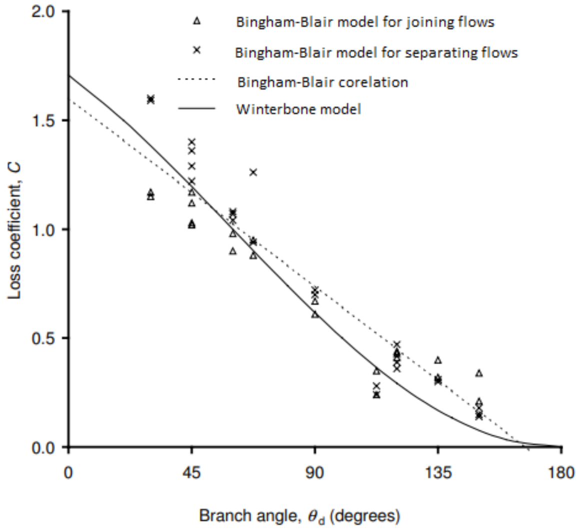

Figure 4: Loss coefficient obtained from the Winterbone Model and Bingham-Blair Model

Figure 6 depicts a comparison for solution of a complex junction using both the constant pressure model by Benson and pressure loss Winterbone model representing the instantaneous pressure for comparison. The simulation was performed on the Lamborghini V-10 engine which has a 5 into 1 exhaust junction classified as the collector type pressure loss junction. The instantaneous pressure results on the duct-1144 in the engine scheme located after the junction are plotted against the crank angle for operating point of 2500 rpm & 100 % Load.

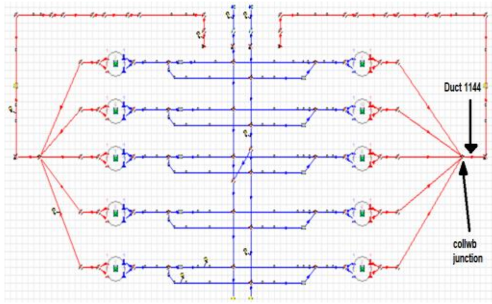

Figure 5: Gasdyn configuration of Lamborghini V-10 engine

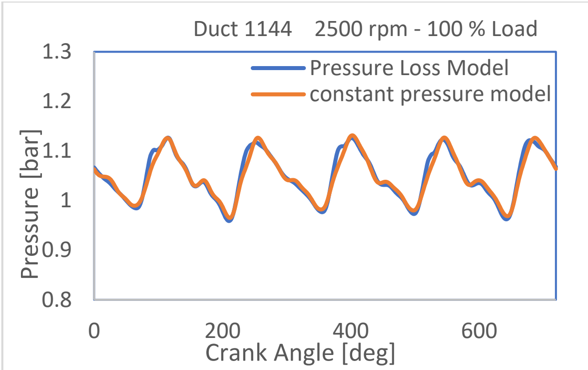

Figure 6: Instantaneous pressure comparison using constant pressure and pressure loss model

Along with the Lamborghini V-10 engine, the V-12 engine configuration was also analyzed for the same purpose, *Figure 6* shows that even for such a complex junction, the constant pressure predicts results in close proximity to the one generated with the pressure loss model. Thus, we can say that the constant pressure model is a simple, efficient, and good approximation for solution of different junction types.

6. Subroutines

Different subroutines are used by Gasdyn simulation tool to solve the junction types involved in the engine configurations. These subroutines are the computational codes and are called in the main program. The subroutine consists of the input variables, main structure & final output variables. The variables and structure of the subroutines differ for each junction type present in the engine scheme.
The scope of this thesis is to analyze all types of subroutines used for the solution of junctions based on the constant pressure model. These include the junction for n-pipes, catalysts junctions, intercooler junctions and the perforates.

The objective is to investigate the functionality, difference, and application of these subroutines for the solution and in the end develop a new subroutine which is general and independent, so that it can alone be used for the solution of all constant pressure model-based junction types.
The subroutines that are used for the solution of boundary conditions at junction types are as follows:

- Subroutine CPMBEN (for junction of n-pipes)
- Subroutine CPMCAT (for junction of pipes connected to the catalyst matrix)
- Subroutine CPMDUC (for junction of pipes connected to the intercooler matrix)
- Subroutine CPMFOR (for perforated ducts)

The above-mentioned subroutines are called in the main Gasdyn program, with multiple input variables to be calculated in the main program before the subroutine is called.
Apart from the multiple input requirement associated with the old subroutines, the structure of the subroutines differ from each other including the procedure adopted for convergence, variables involved and allocated. Also, after the code is passed from the body to the output determination, these subroutines transfer the output to the main program, where further calculations are performed. The flow chart in *Figure 7* depicts how the old subroutine is implemented in the main program

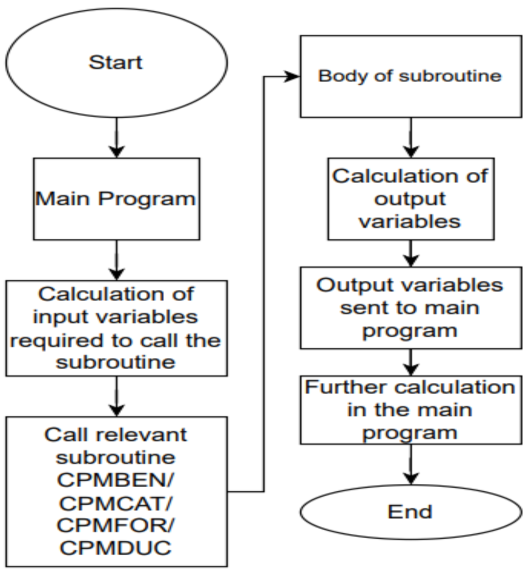

Figure 7: Flow chart for the implementation of the old subroutines

Moreover, the body of each old subroutine differs from each other significantly. The body of subroutine CPMBEN, which is used for the solution of junction of n-pipes is illustrated with the flow chart in *Figure 8*, the structural description of other subroutines are explained in the thesis report in detail

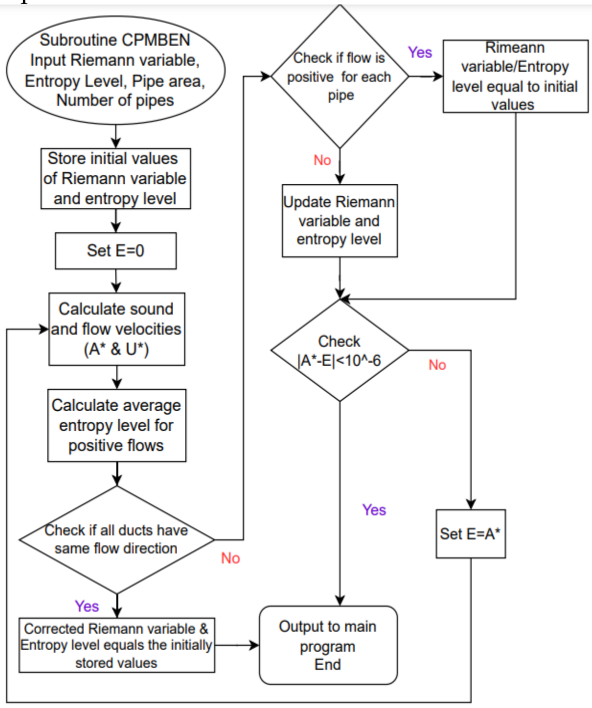

Figure 8: Flowchart depicting the Body of the subroutine CPMBEN

Since the variables involved in each subroutine, the structure and the iterative procedure involved for subroutines CPMBEN, CPMCAT, CPMDUC, CPMFOR is different, but the basic theory behind all these subroutines is the same. It was decided by incorporating the characteristics of each old subroutine to develop a new general routine, which could be called for each of the junction types. Moreover, any improvisation would then be performed on the new subroutine instead of modifying each old subroutine individually.
The new subroutine, which was created by the name of bccpmben, is implemented in the main program as illustrated by the flow chart in *Figure 9*.

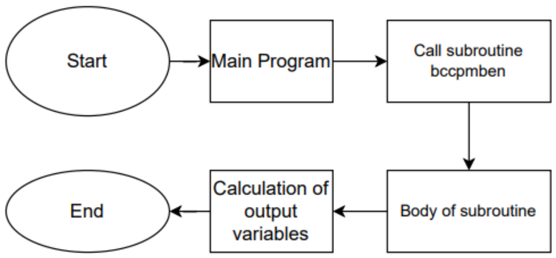

Figure 9: Flow chart for the implementation of the new subroutine bccpmben

The structure of the new subroutine bccpmben ,developed as the main objective of this thesis is represented by *Figure 10*

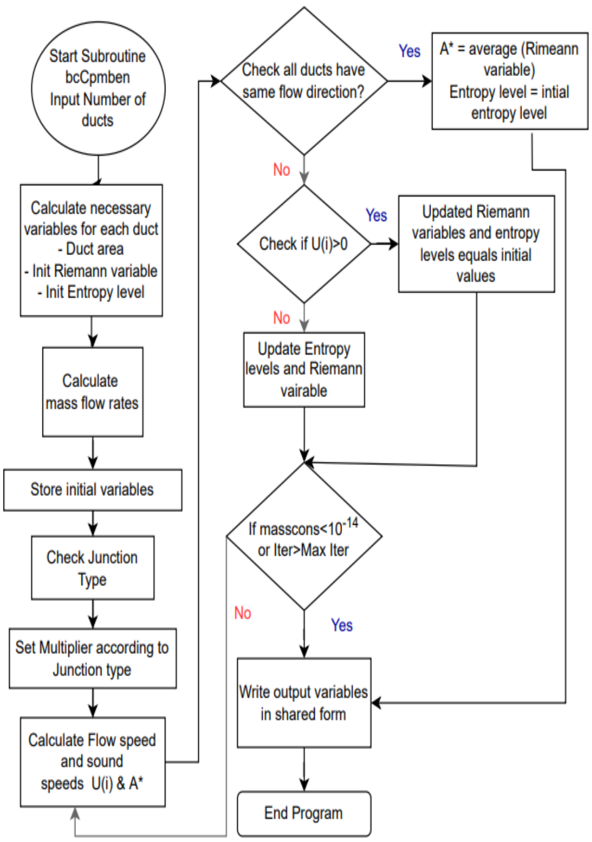

Figure 10: Structural flow chart of the new subroutine bccpmben

After the development of new subroutine, the results obtained were validated by comparing those obtained using the old subroutines, first by individually substituting the old subroutines and comparing, and finally by simultaneously substituting all the subroutines used for the solution of constant pressure model-based junctions by the new subroutine bccpmben. The substitution was performed, and comparison was made on multiple engine configurations and several operating points. The instantaneous properties as obtained after substitution were compared to validate the new subroutine.

One of engine schemes used for comparison named 2.0_16V is represented below

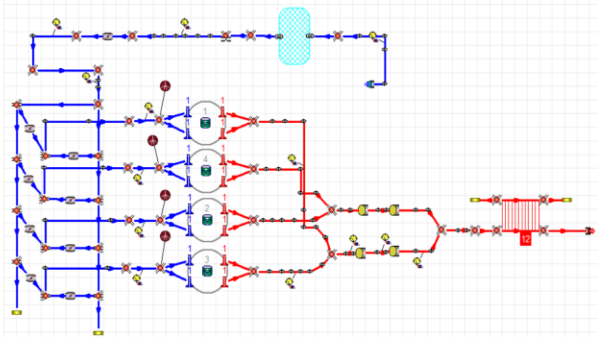

Figure 11: Gas dyn configuration for project 2.0_16V

The engine configuration have the catalysts type, perforates and the n-pipe junctions which were solved by subroutines CPMCAT, CPMFOR and CPMBEN respectively. Hence this project is a good test for substitution of these three subroutines by bccpmben. The results obtained after the implementation of the new subroutine in place of the old subroutines are shown graphically in the following figures.

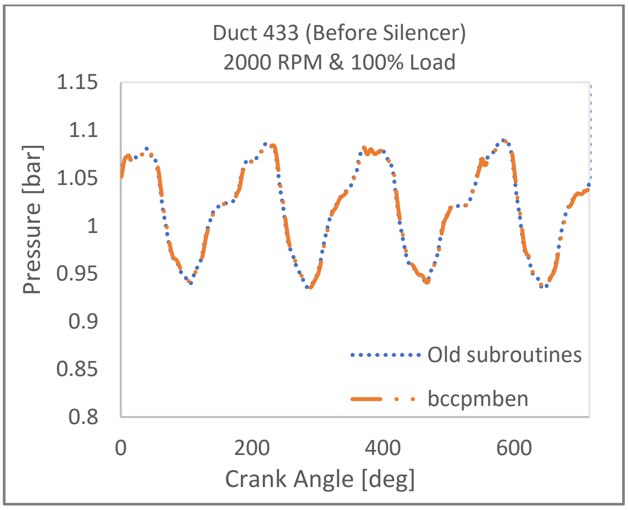

Figure 12: Instantaneous pressure results before and after simultaneous substitution

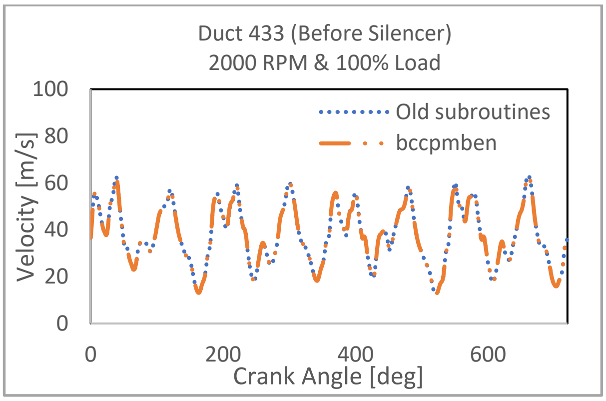

Figure 13: Instantaneous velocity results before and after simultaneous substitution

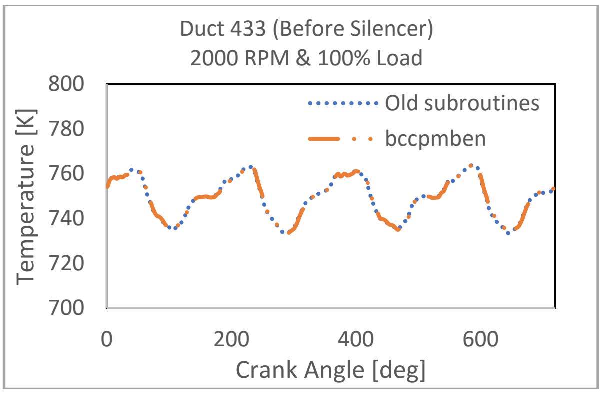

Figure 14: Instantaneous Temperature results before and after simultaneous substitution

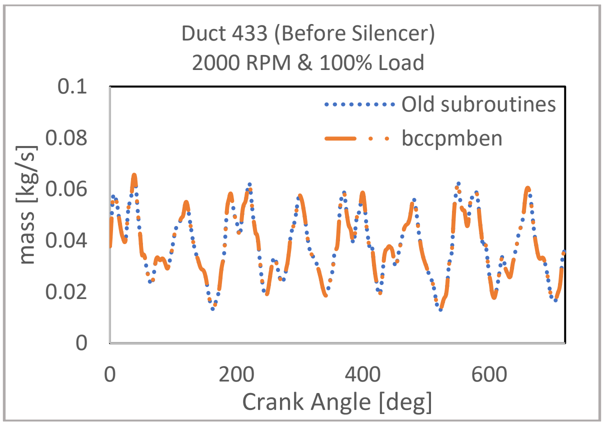

Figure 15: Instantaneous mass flow rate results before and after simultaneous substitution

The result of instantaneous properties including the pressure, mass, temperature, and velocity of fluid for the engine simulation performed on the considered duct with the substitution of the old subroutines by the new subroutine bccpmben are in agreement with the results without substitution which validates that the new developed subroutine is correct and provide accurately similar results across the entire engine cycle. The validation was performed on several other configurations which was found be accurate.

In addition to other features of the old subroutines, the new subroutine also takes into account the mass conservation across the junction and ensures that the total mass flow rate towards the junction is equal to the total mass flow rate that goes away from the junction. This is depicted in *Figure 16* for the same engine configuration across each crank angle

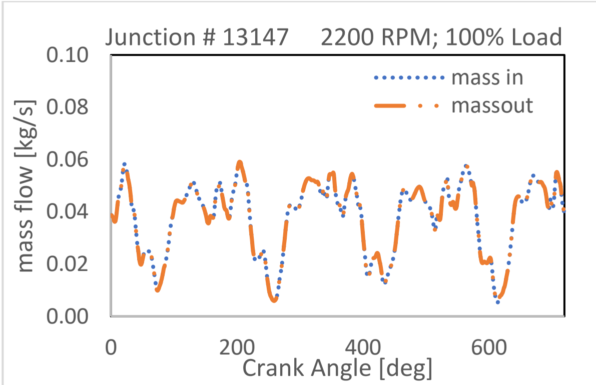

Figure 16: Conservation of mass flow rate for junction using new subroutine bccpmben

The old subroutines showed some instabilities for some particular critical configurations, one of them is represented by *Figure 17*. The engine configuration has one n-pipe type junction in the intake and two silencer junctions in the exhaust manifold, hence the simulation involved the use of subroutines CPMBEN and CPMFOR, which is now replaced by the new subroutine bccpmben.

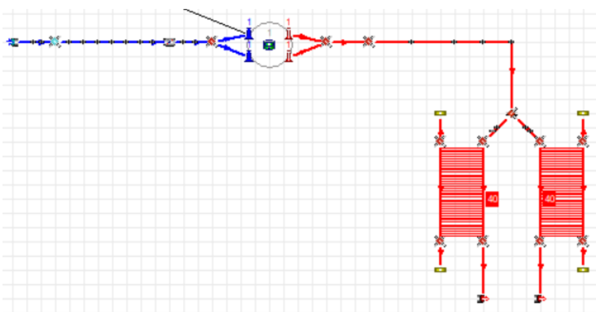

Figure 17: Gasdyn configuration for Project Schighera

The old subroutines were not able to conserve the mass flow rates across the junction at all operating points and also showed pressure instabilities as represented by the engine simulation results shown by the implementation of old subroutines.

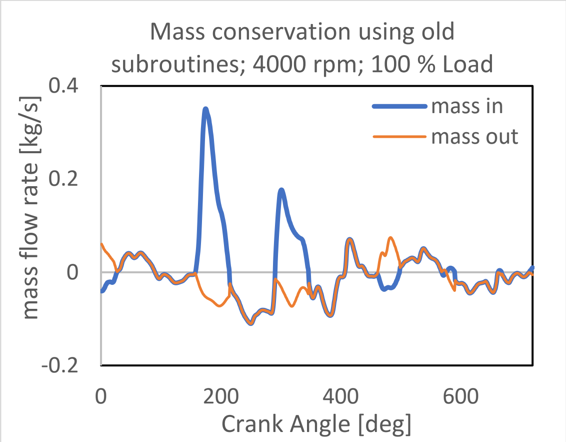

Figure 18: Mass conservation for junction-35 using old subroutines

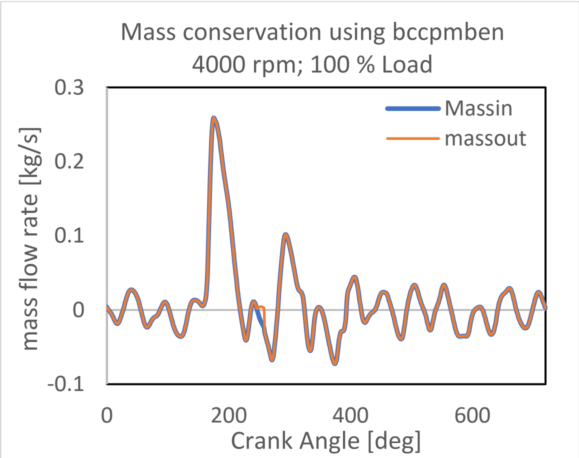

Figure 19: Mass conservation for junction-35 using new subroutine

As observed by *Figure 18 & 19* The mass conservation was respected at all operating points after the implementation of the new subroutine for the engine simulation for this project, which shows that the new subroutine is able to conserve the mass flow rate for the critical projects where the old subroutines failed, thus validating the accuracy of results as obtained by the new developed subroutine. The results represented here are for the operating point of 4000 rpm & 100 % Load. However same scenarios were observed at all operating points, which are presented in the report.

Moreover, instantaneous pressure prediction using the old subroutine showed instabilities across the crank cycle which were eliminated when the new subroutine was used in place of the old subroutines. This can be seen in the instantaneous pressure plotted for the operating points of 2000 rpm & 4000 rpm at full load in *Figure* 20 & *21* where we see pressure instabilities with the use of old subroutine and smooth pressure curves after implementation of the new subroutine, this validates that the new subroutine is able to resolve the instabilities generating by the old subroutines and is more accurate and robust.

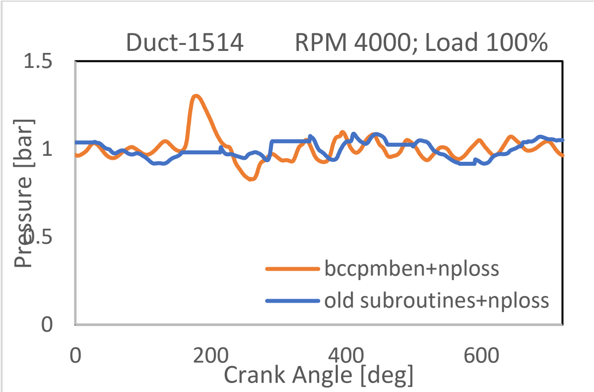

Figure 20: Instantaneous pressure results – Project Scighera at 4000 rpm & 100 % Load

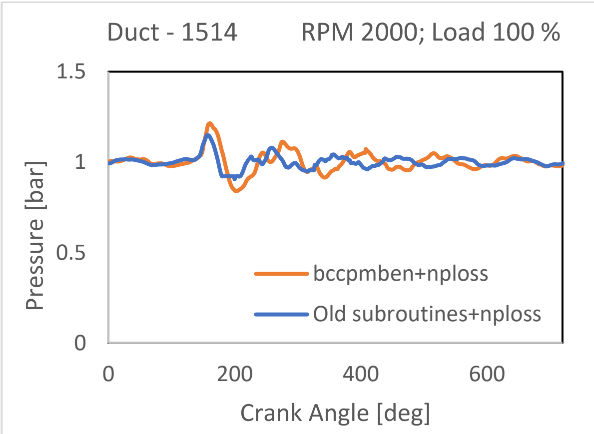

Figure 21*:* Instantaneous pressure results – Project Scighera at 2000 rpm & 100 % Load

7. Conclusions

The new subroutine bccpmben which was developed as the main objective of this thesis to replace the other subroutines being used for constant pressure-based junctions was validated successfully. The new subroutine is more accurate and robust, it has the following features over the old subroutines:

- ➢ The new subroutine bccpmben requires only one input variable that is the number of ducts connected to the junction.

- The subroutine bccpmben can be called for all constant pressure junction types
- Before the calling of the new subroutine, no calculation of variables is required in the main program. The subroutine is capable to calculate the necessary variables inside its body.
- The new subroutine is independent of the main program and can write the output in shared variables, thus unlike the old subroutines it does not require the output to be transferred to the main program for further calculations.
- Any improvement process can be performed by inclusion in the new subroutine instead of modifying each of the old subroutines.
- The subroutine respects the mass conservation accurately across the junction at all operating points throughout the crank cycle
- Instabilities generated for critical projects using the old subroutines were eliminated by the implementation of the new subroutine, which validates the accuracy of the new subroutine

8. References

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