Flownet Nuclear Architecture, Implementation and Verification & Validation

WA Landman, E van Heerden, JP van Ravenswaay and GP Greyvenstein
Faculty of Engineering, Potchefstroom University for CHE
Private Bag X6001, Potchefstroom, 2520, South Africa
Tel: 27 (18) 2994022, Fax: 27 (18) 2991320
e-mail: dinwal@puknet.puk.ac.za

Abstract – *Flownet is a general network analysis code used by PBMR (Pty) Ltd for the thermal-fluid design and analysis of the PBMR plant. It is based on an implicit pressure correction method (IPCM) that solves the continuity, momentum and energy equations (including rotating element dynamics) in large arbitrary structured networks for both steady-state and dynamic analysis. In order to facilitate maximum code re-use and maintainability it was re-developed in an object-oriented paradigm, using C++, within a strict quality system. This paper presents the architectural design, model development, implementation, and verification and validation philosophies used during the development of Flownet. Finally it comments on results obtained with this software package.*

I. INTRODUCTION

The interaction of various thermal-fluid components in an arbitrary structured network is a complex problem to analyse. Yet accurate modelling of these situations is important and imperative in the design of a new power plant, where the interactions cannot be optimised based on passed experience or empirical data. To this end a software package has been developed that can be used in the analysis of this type of network.

The solution algorithms in the previous procedural version of Flownet were developed over an extended period of time and evolved into general network analysis software that can solve arbitrary structured networks for both steady-state and transient cases. Shaft dynamics are also solved as part of the overall solution to the energy, mass and momentum equations [1].

Flownet's capabilities include the simulation of networks such as the PBMR, a high-temperature gas-cooled reactor (HTGR) plant based on a three-shaft Brayton cycle, currently under development by the South African utility Eskom. These dynamic simulations of the complete power conversion unit (PCU) are fully integrated with core neutronics, turbo-machine power matching and controller algorithms[2]. In order for a modelling tool to be used in the design of a nuclear power plant where safety is of the essence, the code had to be rewritten within the framework of a stringent quality control system.

Redeveloping the software also provided an excellent opportunity to implement an object-oriented design and development approach. In order to facilitate maximum code re-use and maintainability, Flownet was re-developed in an object-oriented paradigm, using C++, within a strict quality assurance system. Using classes and grouping classes together in packages, each with well-defined interfaces, enhanced encapsulation and improved maintainability. A persistence mechanism that maps the object-oriented design onto a relational database was devised. Using a relational database has the benefit of open-endedness and having a scientific view of the data.

Model development, implementation, and verification and validation are based on three different processes that have well defined interfaces to ensure a streamline system. Technical teams that specialize either in model development, implementation or verification and validation are responsible for the execution of these processes.

In Flownet the approach used to design the classes and the interaction among them, resulted in a code that was marginally slower than the procedural code that it was based on. The advantage of having an object-oriented code is that profiling can be done effectively. These profiling results have the advantage that CPU intensive code can be easily identified and optimised. Using special techniques to optimise the code, speed improvements of up to 40% were achieved. These speed improvements, to an already fast solving code enables Flownet to perform real time dynamic analysis of large integrated thermal-fluid networks such as the PBMR.

When working on a software package that is being developed and used by a small but very active user base, it is imperative that the configuration management is streamlined and well structured. Practical procedures have been put into place to ensure that anomalies that are logged are addressed and new development continues with the least possible adverse effect on one another.

Numerous thermal-fluid simulations were conducted with the aid of the Flownet software package on a wide variety of networks including both compressible and incompressible flow. These included comparisons with the PBMM (Pebble Bed Micro Model) that was designed using Flownet. The comparisons between Flownet and both analytical and experimental results proved to be excellent.

II. BACKGROUND TO FLOWNET

The complexity associated with the thermal-fluid design of closed-loop cycles requires the use of a variety of analysis techniques and simulation tools. These range from simple one-dimensional models that do not capture all the significant physical phenomena to large-scale three-dimensional CFD codes that, for practical reasons, cannot simulate the entire plant as a single integrated system. Flownet is a code that provide a good compromise between accuracy and speed. Its distinquising features are as follows:

- Easy to use graphical user interface, where networks can be created and edited.
- Flownet can handle a wide variety of network component models including pipes, turbo-machines, pumps and fans, a number of heat exchangers, orifices, reactor models and valves.
- PID and other controllers.
- In addition to its fluid dynamics and heat transfer capabilities, Flownet also features a one-dimensional solid heat transfer modelling capability with which heat transfer through solid structures can be modelled.
- Both steady-state and dynamic analysis of large arbitrary structured thermal-fluid system.
- Gas mixture concentration solver.
- Turbo-machine power matching.
- A general external control interface which allows the use of other software packages such as Simulink and Matlab to design and simulate advanced plant control.
- Direct design functionality that can be used to perform design analysis.
- Sensitivity analysis that is based on the Monte Carlo algorithm.
- The code has been extensively verified and validated in industry for a number of years.
- Very fast steady-state solution times.
- Perform real-time dynamic analysis of large arbitrary structured thermal fluid system.[3]

During the early stages of the PBMR project it was decided to re-develop Flownet. Its predecessor was developed in procedural C code using text files for data storage. The objectives of the redevelopment of Flownet were the following:

- Develop the code within the framework of a strict quality assurance system.
- Improve maintainability of a large and complex code.
- Maximize code re-usability.
- Use of relational database technology to improve the data persistance mechanism.
- Give the code a real Windows look and feel.
- Based the new development on exactly the same solution algorithm and have all the capabilities it predecessor possessed.
- Retain the solution speed and flexibility of its predecessor.

In the next section a brief outline of some of the architectural issues will be given.

III. ARCHITECTURAL DESIGN

There were a number of preconditions that existed when the redevelopment started:

- The program was to be written in C++ in an object-oriented paradigm.
- A relational database had to be used to store the network data as well as the repository of characteristics such as fan and pump curves, turbine and compressor maps, etc.
- The target operating system chosen was Windows®.

It soon became apparent that one large monolithic executable was not going to be very practical. One large program implied longer compile-debug cycles and longer built times that impacted on the productivity of the development group. The program was therefore divided up into packages.

In object-oriented terminology a package is a collection of classes collaborating to implement the functionality that is associated with the package. Each package represents a functional area in Flownet and is mapped to a dynamically linked library (DLL) on the Windows platform. Each package has well-defined interfaces that enhances encapsulation and improve maintainability.

A persistence mechanism was devised to map classes in the object-oriented design onto tables in a relational database. A design pattern of mapping each class to a table in the database, and every data member of a class to a field in the table was adopted. Each class that needs interaction with the database was given the responsibility of doing so by implementing the appropriate methods.

Using a relational database for this kind of data is somewhat of an overkill. It takes longer to save large volumes of data to a relational database than it takes to save the corresponding data to an ASCII file. However, the relational technology provides a structured way to organize data and to filter that data. The availability of third party tools to view and edit the data gives the added benefit of open-endedness. These benefits far outweigh the mentioned drawback.

IV. NEW MODEL DEVELOPMENT

Model development, implementation and verification and validation form a integrated process, as part of the quality assurance of Flownet, to ensure that the development and implementation of new models into Flownet are controlled and streamlined.

IV.A Model development

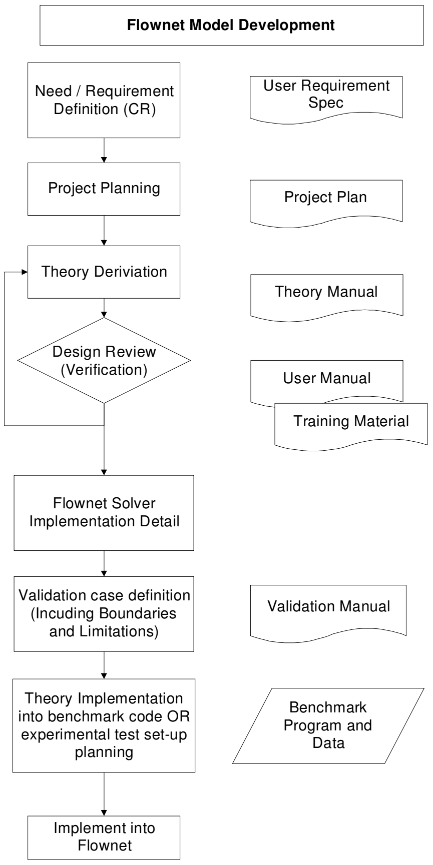

Flownet Model Development
Need / Requirement Definition (CR)
User Requirement Spec
Project Planning
Project Plan
Theory Deriviation
Theory Manual
Design Review (Verification)
User Manual
Training Material
Flownet Solver Implementation Detail
Validation case definition (Incuding Boundaries and Limitations)
Validation Manual
Theory Implementation into benchmark code OR experimental test set-up planning
Benchmark Program and Data
Implement into Flownet

Figure 1: Model development flow chart.

Model development consists of the process of refining a user requirement into a theoretical model to be implemented into Flownet.

During this process theory is derived for a new model after which it is peer reviewed. The next step is to rewrite the theory into the Flownet solver format for implementation. A validation case is then formulated and a benchmark is developed. The benchmark can consist of a simple hand calculation, a numerical solution or experimental data. In parallel with this, the various documents required are developed. The next step is to implement the new model into Flownet.

IV.B Model Implementation

The first step of the model implementation phase is to investigate the impact the new model has on the existing architecture and to update the architectural design documentation, if needed. Next the detail design and implementation documentation is generated.

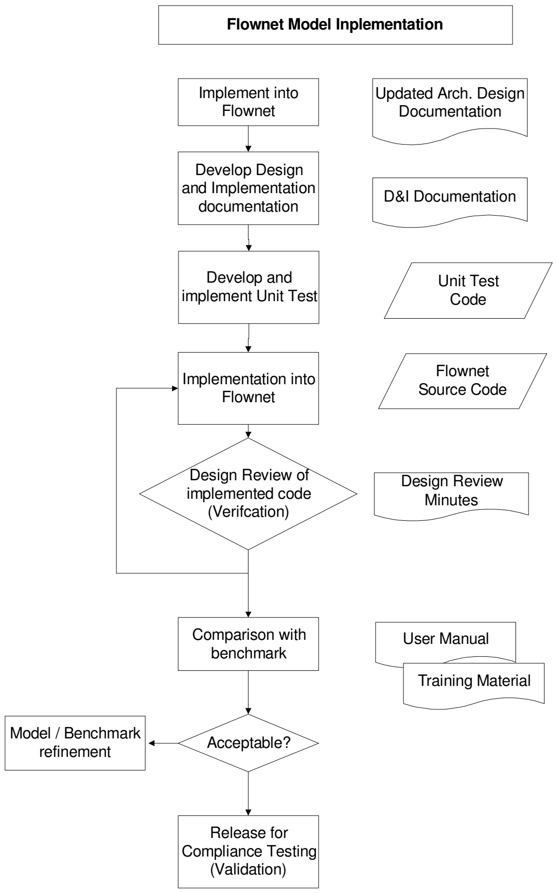
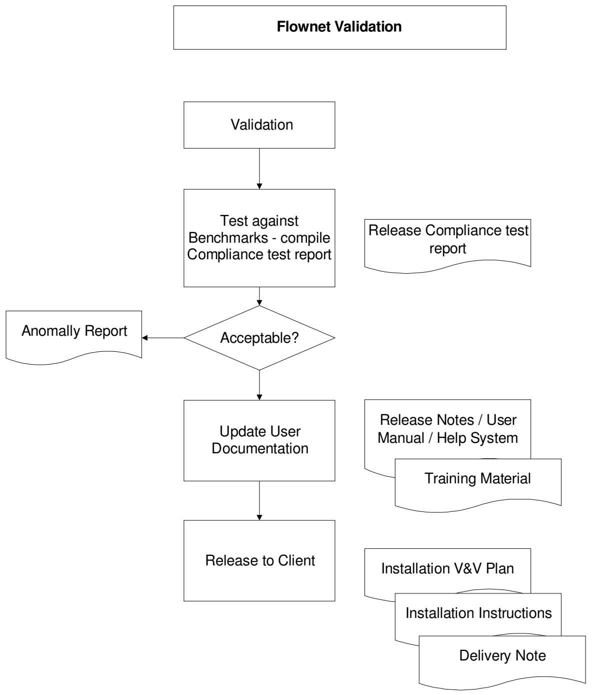

Flownet Model Inplementation
Implement into Flownet
Updated Arch. Design Documentation
Develop Design and Implementation documentation
D&I Documentation
Develop and implement Unit Test
Unit Test Code
Implementation into Flownet
Flownet Source Code
Design Review of implemented code (Verifcation)
Design Review Minutes
Comparison with benchmark
User Manual
Training Material
Model / Benchmark refinement
Acceptable?
Release for Compliance Testing (Validation)

Figure 2: Model implementation flow chart.

To ensure code integrity, unit tests for the new model are already defined and implemented at this point. The next step is the physical implementation of the new model into the Flownet source code. Implemented code is submitted to stringent design reviews to ensure that the derived models have been correctly translated into computer code. At this point a preliminary comparison with the stipulated benchmark is performed. The outcome of this step could result in refinements to the model or the benchmark. Successful preliminary testing leads to the release of Flownet for compliance testing (validation).

IV.C Verification and Validation

Verification is performed during the model development and implementation phases through the design and peer review processes. The final step before releasing Flownet to the client is to validate the newly implemented model against the benchmark specified in the model development phase.



Flownet Validation
Validation
Test against Benchmarks - compile Compliance test report
Release Compliance test report
Anomally Report
Acceptable?
Update User Documentation
Release Notes / User Manual / Help System
Training Material
Release to Client
Installation V&V Plan
Installation Instructions
Delivery Note

Figure 3: Model validation and verification flow chart.

If the results obtained with Flownet are within the specified tolerances from the benchmarks, the code is deemed acceptable, all relevant documentation is updated and Flownet is released to the client.

V. CODE OPTIMISATION

One of the intended end uses of the newly developed code is as part of a simulator for training and engineering analysis purposes.

It is imperative that real-time (or faster) simulations can be achieved for training simulators. On currently available "general purpose" hardware, simulation times are marginally slower than real-time for a realistically sized problem. For this reason an effort was made to increase the performance of the program.

Increasing the performance of any computer program can be broadly classified into two categories, namely algorithm improvements and code tweaking.

Algorithm improvements should always be tried first when code optimisation is considered. The reason for this is that if one has an algorithm that has a complexity of $O(n^3)$, and there is another algorithm available that essentially solves the same problem but is of complexity $O(n^2)$, then no amount of code tweaking will provide comparable benefits to replacing the algorithm for large enough problems (i.e. large enough n). Thus the first step is to make sure that all the algorithms are as efficient as possible.

When it comes to code performance enhancement there are two schools of thought. The first is that one designs with efficiency in mind from the outset. The second is that one firstly designs for clarity and maintainability and then improves performance of the code. The code that should be considered for performance improvements should be identified by actual measurement in a representative size problem.

Donald Knuth[4] observed that premature optimisation is the root of all evil. Furthermore, it is generally accepted that programmers have a very bad intuition for where bottlenecks lurk within their code, thus frequently spending hours optimising code that very rarely gets executed.

Heeding that warning, the approach that was preferred in the redesign process was to firstly design for maintainability and clarity. Code speed improvements were only attempted on code where performance profiling pointed to the existence of a bottleneck(s).

The first round of profiling pointed to the matrix solver as the largest consumer of CPU cycles. The calculation of pressure correction terms in the solution algorithm requires the improved accuracy that is associated with matrix methods.

Since a state of the art matrix solver for sparse matrices is already used, and the fact that we could not use an iterative approach for solving the pressure correction equations, it was concluded that the code needed to be optimised rather than changing the matrix solution algorithm.

Guided by the profiling tool and zooming in on the detail of the matrix algorithm, it was found that considerable CPU time was spent on the setting up of the connectivity of the matrix. This connectivity did not change from one pressure correction calculation to the next, but the same matrix code was used for solving the temperatures in the energy conservation equations. So the storage of the connectivity was therefore encapsulated into a matrix class and an instance of the matrix class created for each set of equations that needs to be solved. This allowed for the storage of the connectivity data rather than recalculation of it at each matrix solution.

This approach led to a performance gain of 9.3% in a typical large network. As is the case with most engineering solutions a compromise had to be made. Using a technique of caching results, so that it can be used again, uses more memory in order to gain some speed advantage. A second opportunity for performance enhancement was identified as the calculation process of Mach numbers at the nodes. Again the bottleneck was identified by the use of a performance profiler.

In the original code, the Mach-numbers were calculated at each node and after each iteration. There are places in the solution algorithm where these Mach numbers were used, and they were also printed as part of the results. Here the solution was obvious. Instead of calculating the Mach number upfront, the Mach number was invalidated after each iteration and then re-calculated as needed. For the majority of the nodes this resulted in the Mach number being calculated only once during the printing of the results.

This is a technique known as lazy-evaluation, and in this case led to performance improvements of 8.9% for a typical large network. Again there was a compromise of a slightly more complex solution but with the benefit of performance gains.

There were various additional situations, all identified by actual performance profiling that led to various performance gains. Almost without exception some clarity, simplicity and code maintainability were lost for the sake of performance. The benefit, however, is that the changes have been introduced where it resulted in undisputed benefits.

In Table 1 the results from a typical network is shown before and after the performance enhancements were made.

	Procedural program	***Before optimisation***	***After optimisation***
With graphical output	16.843	26.052	15.820
Without graphical output	16.527	19.033	14.286

Table 1: Optimisation comparison between procedural and object oriented code.

From the table one can see that there has been a 25% improvement in simulation times where the solver is invoked without output, and a 40% improvement where graph plotting is involved. Furthermore the difference in performance between an equivalent procedural program is also given. After optimisation there is a speed improvement of 6% when the output is given and 13% when the graphs are not plotted.

It should be pointed out that the graphs for the new code is much more feature rich than the procedural code that gave rise to a big performance concern. The optimisation of the graphing functionality was not discussed in the section on performance enhancements since it relates to user interface issues and as such is platform specific, but there was significant performance gains introduced in the graphing functionality too.

At this point a realistic question is whether real-time simulation have been achieved yet? The answer: "It depends". In this case it depends on the size of the problem and the price of the hardware, but for a representative sized problem with higher end generally available hardware, real-time simulation can be achieved.

There is still scope for more performance enhancements. Two options that come to mind are using iterative matrix algorithms for the temperature solver and parallelization of the code. These will be addressed in the future as the need arises.

VI. CONFIGURATION MANAGEMENT

VI.A Code configuration management (SourceSafe)

The Flownet code configuration management is done with the assistance of Visual SourceSafe®, a Microsoft® product. For developers at different locations a web based third party software product is used that allows these users to access the Flownet source code on the SourceSafe server. The software used has the following capabilities:

- Provides the users with easy to use graphical user interfaces for both the server and client applications.
- It keeps advanced history tracing of all activities related to Flownet source code under configuration management.
- It allows multiple user accounts with adjustable levels of access rights assigned by the system administrator.

The Flownet release cycle is divided into major and minor releases. Minor releases are usually associated with bug fixes while major releases, on the other hand, are associated with new model development. The duration between major releases is usually in the order of four to six months.

In order to ensure that new developments that are currently underway do not introduce unwanted anomalies into the released code the following system is used:

Directly after a major release the source code on the SourceSafe server are branched into two different sets of identical code. The one is labelled *Production Code* and the other one is labelled *Development Code.* The production code is associated with bug fixes and the development code is associated with the new functionalities that will be introduced during the development cycle leading up to the next major release. During minor releases, after an anomaly was reported and fixed on both the production and development code, the production code is taken from the server, built and released for testing. If the tests are successful it is released to the client. By the end of a major release life cycle the production code and development code are merged with one another, built and released for testing. If these tests are successful a major release is done to the client. The development code on the server is then branched and a new development/release cycle starts.

VI.B Anomaly Reporting (AR) and Change Requesting(CR)

In order to streamline these supporting system for a code with an international user base, a web based reporting system was developed. This system has the advantage that users can track either AR's or CR's as they move through the system. The figures below present the flow path for these processes.

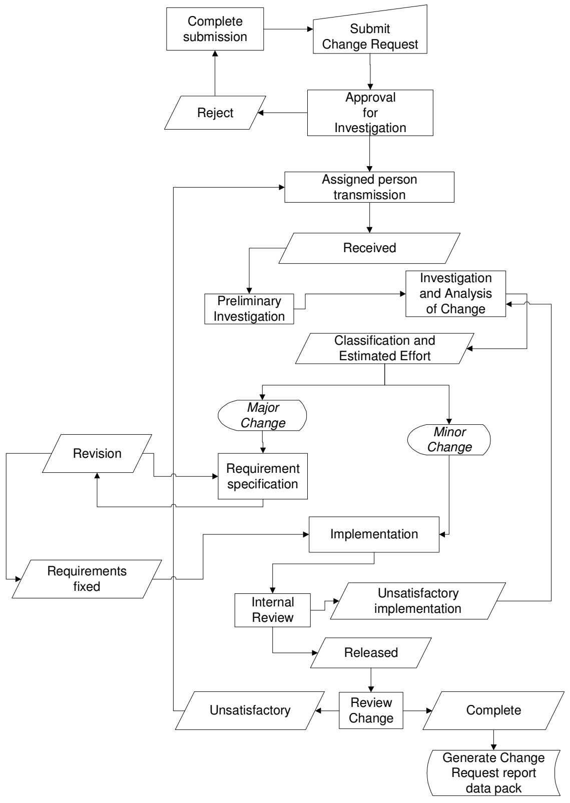

Complete submission
Submit Change Request
Reject
Approval for Investigation
Assigned person transmission
Received
Preliminary Investigation
Investigation and Analysis of Change
Classification and Estimated Effort
Major Change
Minor Change
Revision
Requirement specification
Implementation
Requirements fixed
Internal Review
Unsatisfactory implementation
Released
Unsatisfactory
Review Change
Complete
Generate Change Request report data pack

Figure 4: Anomaly reporting flow chart.

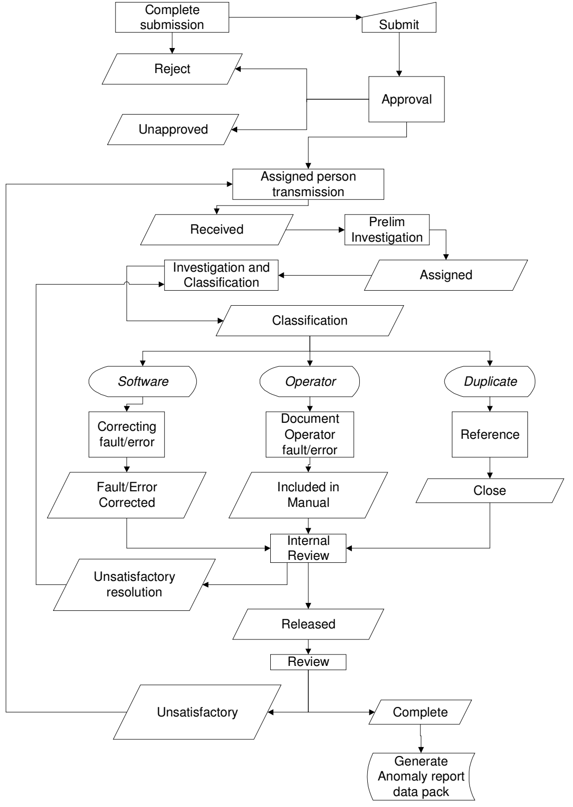


Figure 5: Change requesting flow chart.

VII. RESULTS

Numerous thermal hydraulic simulations were conducted with the aid of the Flownet software package on a wide variety of networks including both compressible and incompressible flow. These included comparisons with the PBMM that was designed using Flownet.

The validation cases are presented as follows: Firstly a short description of the problem that was modelled is given. Secondly the results are compared to results obtained with other codes or to experimental data. Finally a short discussion of the results is given. In all the cases the Flownet results are presented by the markers only and the results of the validation case by the solid line.

VII.A Pipe with pressure waves

This example shows a compressible pipe element with an inlet pressure of 300 kPa and an outlet pressure of 100 kPa. During a transient event a valve at node 2 (outlet) is closed instantaneously. The comparison between the pressures and temperatures calculated with Flownet, an implicit pressure correction method (IPCM) and with an explicit code (EX) are shown in Figure 7.

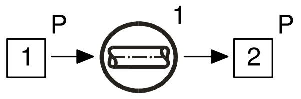


Figure 6: Flownet graphical presentation of pipe element.

The system specifications are as follows:

Pipe 1	
Number of Increments	20
Length [m]	100
Diameter [mm]	100
Node 1	
Pressure [kPa]	300
Node 2	
Pressure [kPa]	100

Table 2: Pipe system inputs.

From the comparison it can be seen that the results of the two codes compare very well. The explicit code (XNET) that was used to solve the problem is based on a 4th order Runge Kutta solution algorithm.

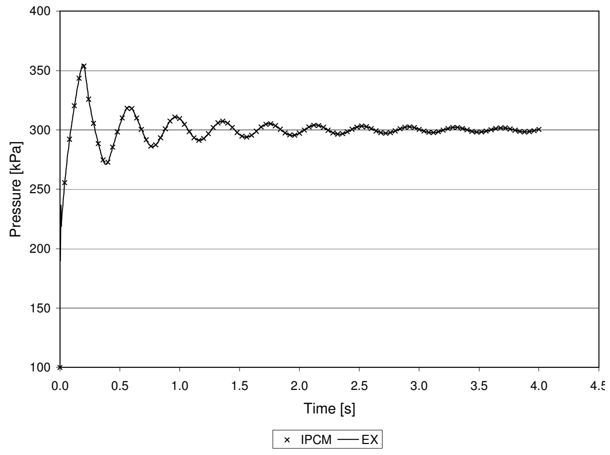


Figure 7: Pressure at the end of a 100 m long pipe due to the sudden closure of a valve at the downstream end of thr pipe.

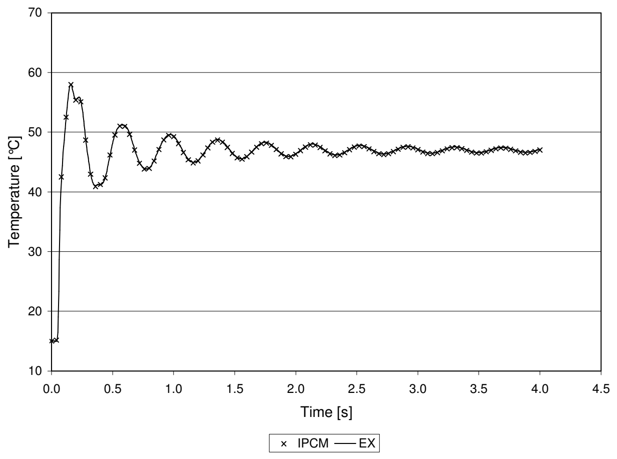


Figure 8: Temperature at the end of 100m long pipe due to the sudden closure of a valve at the downstream end of the pipe.

VII.B Tanks blowing down

This example shows a number of tanks that have been pressurized to specific pressures. Starting at steady state, valves at tanks 1, 3 and 4 are opened instantaneously and the response of the system are modelled by both Flownet (IPCM) and by a code based on an explicit solver (EX). The figure below shows the graphical layout of the network as presented in the Flownet GUI.

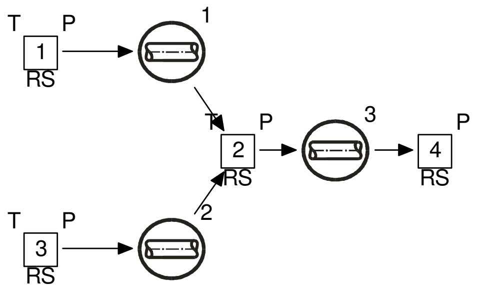


Figure 9: Flownet presentation of a blow down tank system.

The system specifications are as follows:

Pipe 1	
Number of Increments	20
Length [m]	100
Diameter [mm]	100
Pipe 2	
Number of Increments	20
Length [m]	100
Diameter [mm]	100
Pipe 3	
Number of Increments	20
Length [m]	100
Diameter [mm]	100
Node 1	
Volume [m^2]	10
Pressure [kPa]	300
Temperature [˚C]	100
Node 2	
Volume [m^2]	10
Pressure [kPa]	150
Temperature [˚C]	15
Node 3	
Volume [m^2]	10

Pressure [kPa]	250
Temperature [˚C]	50
Node 4	
Volume [m^2]	10
Pressure [kPa]	100

Table 3:Blow down tank system inputs.

The graphs below shows the pressure and temperature response of the system as calculated by both Flownet and the explicit solver.

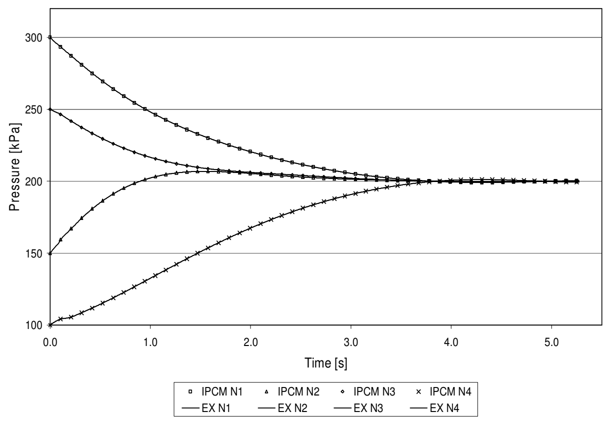


Figure 10: Pressure transient in a blow down tank system.

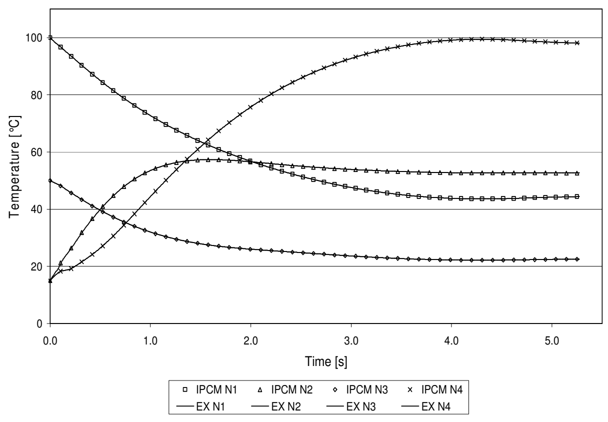


Figure 11: Temperature transient in a blow down tank system.

VII.C Temperature transient in a recuperator

In this example a recuperator with a total heat transfer area of 300 m^2 and a thermal capacitance of 9 kJ/K is considered. The hydraulic diameter and cross flow area of both conduits are 0.5 m and 0.1963 m^2 respectively. Both the hot and cold fluids are helium at an inlet pressure of 700 kPa and an outlet pressure of 670 kPa. Initially the total inlet temperature of both streams is 300 ˚C. Starting at steady-state conditions, the total inlet temperature of the hot stream is stepped to 500 ˚C at time $t = 0$ s.[5]

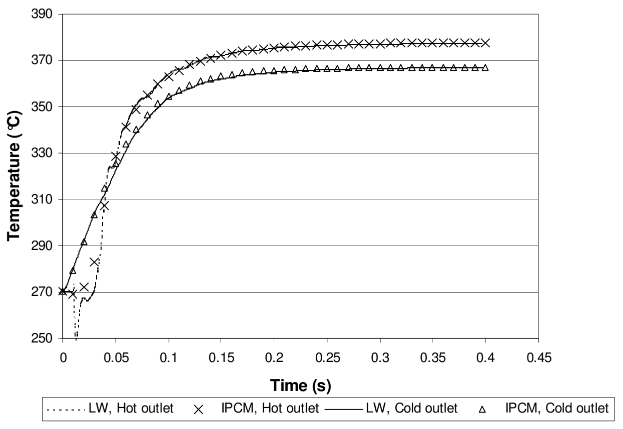


Figure 12: Recuperator exit temperature due to a temperature step at the inlet of the hot stream for a counter flow configuration.

Figure 12 shows the outlet temperatures with time of the hot and cold streams for a counter flow arrangement. The results of the IPCM are compared to that of the two-step Lax-Wendroff (LW) method.

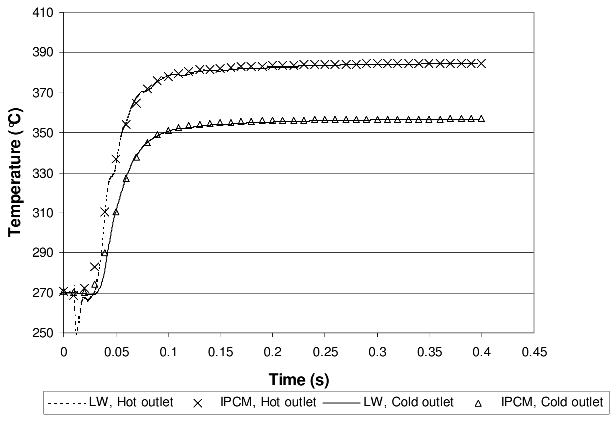


Figure 13: Recuperator exit temperature due to a temperature step at the inlet of the hot stream for a parallel flow configuration.

The LW method shows a fluctuation in the hot outlet temperature shortly after the beginning of the transient. After about 0.03 s the curve becomes smooth with a very good agreement between the IPCM and the LW method.

Figure 13 shows the outlet temperatures with time of the hot and cold streams for a parallel flow arrangement. Again the agreement between the IPCM and the LW method is very good apart from the temperature fluctuation of the LW method at the start of the transient[5].

VII.D Pebble Bed Micro Model start-up (PBMM)

This example presents the comparison of Flownet with the pressure over the start-up blower during the start-up of the PBMM. The drawing below shows the graphical layout of the model.

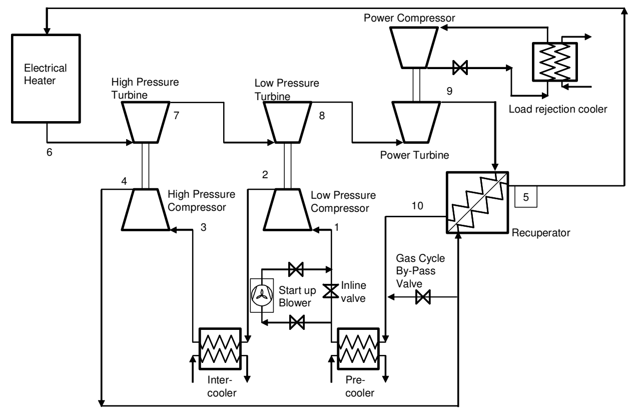


Figure 14: Pebble Bed Micro model graphical layout.

During start-up the inline valve (IV) is closed and the start-up blower system (SBS) is used to circulate the gas through the cycle. The SBS is a positive displacement device, thus the flow-rate remains essentially constant. Heat is then added to the gas in the heater. This energy is converted in the turbines into shaft work to power the compressors. For start-up, the power to the heater is kept constant at about 180kW. As the system heats up, the outlet temperature of the heater rises as the inlet temperature rises and the pressure increase across the IV drops. The cycle spirals towards self sustained circulation and the SBS is disengaged when the pressure drop over the valve is 0 kPa. At this condition the cycle is said to have bootstrapped.

The exit temperature of the heater is probably the most important determinant of the bootstrap point as the energy that the turbines can deliver, depends on the inlet gas temperature. An estimation of the bootstrap temperature was made by calculating with Flownet the pressure increase over the IV as function of heater outlet temperature. In Figure 14 a comparison between the calculated and measured variables can be seen.[6]

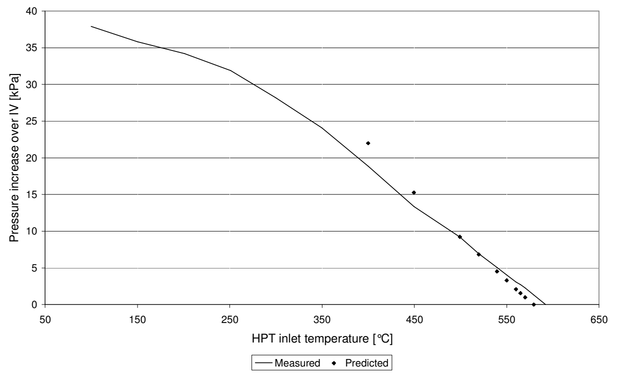


Figure 15: Pressure difference across the inline valve as a function of the heater outlet temperature.

VIII. CONCLUSION

This paper presented the architectural design, new model development and validation and verification required during the redevelopment of Flownet, a thermal fluid tool that is used to solve complex thermal fluid systems. Advanced optimisation techniques was used to improve the solution time to such an extent that real-time simulation of realistic networks are possible. In order to successfully manage a code based in a large development team, a number of practical procedures needs to be used to ensure proper configuration management. The newly developed code was validated against a number of benchmarks. These comparisons proved to be extremely good.

ACKNOWLEDGMENTS

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