VERIFICATION AND VALIDATION OF A THERMAL HYDRAULICS CODE USED TO MODEL THE PBMR

F. Botha and G.P. Greyvenstein

Thermo Hydraulic Analysis Group, PBMR, Lake Buena Vista Building,
1267 Gordon Hood Ave., Centurion 0046, South Africa
derick.botha@pbmr.co.za

SUMMARY

Flownex is a general-purpose thermal-fluid network analysis code used as a tool in the design of the Pebble Bed Modular Reactor. The National Nuclear Regulator requires the use of benchmarks to Verify and Validate (V&V) such a design code. This paper covers the verification and validation of selected fundamental components and aspects in Flownex. Attention is also given to the integration of these components to verify and validate their use in arbitrary structured thermal-fluid networks.

1. INTRODUCTION

Flownex is a general-purpose thermal-fluid network analysis code that solves the flow, pressure and temperature distribution in large unstructured thermal-fluid networks. This provides the engineer/designer essential information on the interaction between network components and the behaviour of complex systems.

An important design application is the modelling of the Main Power System (MPS) of the Pebble Bed Modular Reactor (PBMR). Various PBMR operating conditions and transients are simulated using Flownex. These transients include system start-up, loss of load and the simulation of abnormal events such as pipe breaks. To ensure a sound design it is imperative to ensure that the Flownex model of the PBMR produces correct results.

According to Licensing Guide (LG) 1038 [6] the National Nuclear Regulator (NNR) requires the use of benchmarks to Verify and Validate (V&V) the code. In this context validation can be seen as the evidence that demonstrates that the analysis tool is fit for its purpose. This implies demonstrating that Flownex gives accurate results for typical situations encountered during the design process. Verification is defined as the process of ensuring that the governing physical equations have been correctly translated into computer code. Validation is of no consequence without verification. However if the governing physical equations are applicable and their implementation verified this implies some measure of validation. In this paper fundamental aspects of Flownex are V&V'd using benchmarks. This work was done as part of a master's thesis in addition to the formal V&V process followed by the code developers [3].

2. SCOPE OF VERIFICATION AND VALIDATION

For thorough V&V it is important to focus on specific aspects of a network before considering the results of more complex problems. In this manner the cause of an anomaly can more easily be identified. Fundamental aspects and components that were V&V'd are pipe elements, boundary conditions, loss factors, heat transfer, quasi-steady elements, tanks and junctions. A theoretical overview of some of these components will now be given.

The one-dimensional differential equations governing transient flow through a variable area ***pipe*** are

Continuity:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho VA)}{A\partial x}=0 \tag{1}$$

Momentum:

$$\frac{\partial(\rho V)}{\partial t}+\frac{\partial(\rho V^2 A)}{A\partial x}+\frac{\partial p}{\partial x}+\rho g\cos\theta+\frac{f\rho V|V|}{2D}=0 \tag{2}$$

Energy:

$$\frac{\partial}{\partial t}(\rho u_0)+\frac{\partial\{(h_0+gz)\rho VA\}}{A\partial x}-\dot{q}=0 \tag{3}$$

where h_0 is the total enthalpy defined as $h_0=h+\frac{1}{2}V^2$ and u_0 is the total internal energy defined as $u_0=u+\frac{1}{2}V^2$. It is the way in which these equations are solved that determines the characteristics of a particular method. For Flownex the solution methodology is described in [1]. Elements with such a set of governing equations that implies spatial discretization will be referred to as distributed elements. A similar set of equations exists for distributed heat exchanger modelling in Flownex.

Compressors, turbines, valves, orifices and pumps are typical ***quasi-steady element*** models in Flownex [4]. In such elements the flow is only dependent on boundary conditions at the current time step. Only an orifice element was considered for this study. This will be sufficient to validate the general integration methodology of such elements into Flownex. For a simple orifice model the total pressure drop is dependent on the inlet density and velocity (Equation (4)).

$$\Delta p_0=\tfrac{1}{2}k\rho V^2 \tag{4}$$

With no heat transfer or work acting on the fluid the total temperature across an orifice remains constant.

For ***tanks*** only continuity and energy conservation apply. With zero velocity assumed in a tank the momentum conservation equation falls away. A control volume form of Eqs. (1) and (3) gives the appropriate governing equations.

Junctions (or nodes) refer to the connection of an arbitrary number of distributed and/or quasi-steady elements. Junction models should also satisfy conservation of mass, energy and momentum. Using junctions all other components can be integrated into a thermal-fluid network. Tanks can be implemented as a special case of a junction model.

Once these fundamental components are V&V'd, benchmarks can be performed on the integration of these components into simple arbitrary structured networks.

3. BENCHMARKS

Two methods were used as benchmarks. In case of a difference between one method and Flownex the second method can then be used as an additional check. It was decided to select a commercial code as a benchmark, and to implement an explicit method.

RELAP5, developed for best-estimate transient simulation of light water reactor coolant systems during postulated accidents, was selected as the commercial benchmark code. The US NRC gave permission that the code may be used for this study. Unfortunately the code has not been used extensively to model Helium systems. RELAP5 uses either a semi-implicit or a nearly implicit numerical method. RELAP5 and Flownex use numerical schemes applied to staggered grids. Flownex uses a derivative of the Implicit Pressure Correction Method developed by G.P. Greyvenstein [1].

Using C++ the Lax-Wendroff method was implemented as the second benchmark method. This method has been used extensively to model transient flow in internal combustion engines [5]. It is an explicit method applied on a co-located grid.

4. BENCHMARK TEST CASES

Various test cases were defined to thoroughly test selected fundamental components and aspects for steady and transient flow. Only selected test cases are presented in this paper. For all test cases helium was used as the working fluid. (R = 2080 J/kg.K, C_p = 5200 J/kg.K, μ = 0.0002 kg/m.s). Where applicable the number of sub-increments in each case was chosen large enough to ensure a grid independent solution.

A large number of steady-state comparisons were done between Flownex, RELAP5, Lax-Wendroff and analytical results for different pipe flow scenarios. Pipe mass flow vs. pressure drop for the following pipe geometry is given in Figure 1.

Length (m)	**Diameter (m)**	**Roughness (e/D)**	**Forward k-loss**	**Reverse k-loss**
10	0.1	$3\text{x}10^{-5}$	0	1

Table 1: Pipe geometry for steady-state flow benchmark

For this benchmark the reverse flow k-loss is equally distributed between all sub-increments. For example, a k-loss of 0.1 for each of 10 sub-increments. All pipes in this paper were simulated with this same roughness. In Figure 1 comparisons were done for adiabatic (Adi) flow and flow with positive (Q+) and negative (Q-) heat transfer. For forward and reverse flow the inlet total pressure and total temperature was fixed at 700 kPa and 15ºC respectively. The outlet pressure was varied between 500 and 700 kPa for forward and reverse flow. For each steady-state the heat transfer was fixed in order to give an outlet total temperature of –85ºC (Q-) or 1015ºC (Q+).

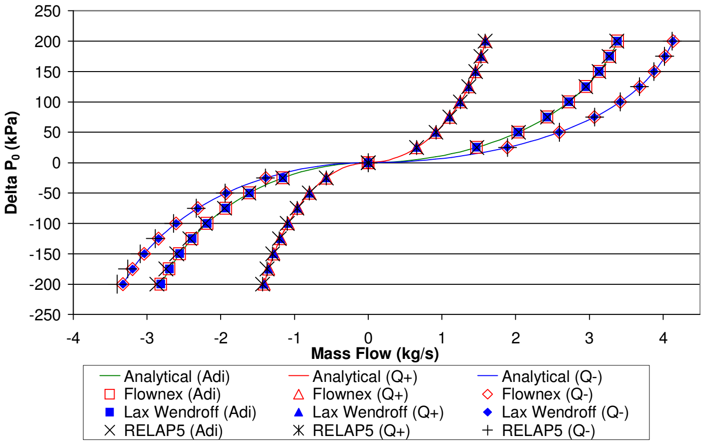

Figure 1: Steady-state mass flow vs. total pressure drop in a pipe

Results for adiabatic transient flow in a pipe are shown in Figure 2. Once steady-state conditions are reached in the pipe a valve is closed at the downstream end of the pipe. Steady-state conditions were reached by using an upstream total temperature and pressure of 15ºC and 5100 kPa respectively. Total pressure at the downstream end was set to 4000 kPa. Exactly the same pipe geometry as in Table 1 was used. In Figure 2 the total pressure and temperature at the closed end are compared for each code.

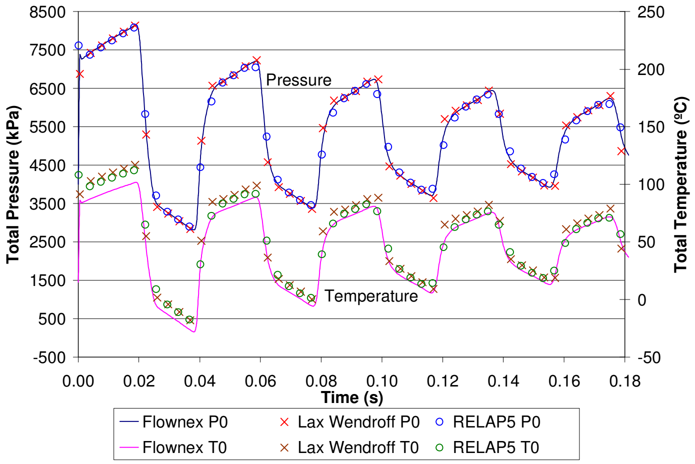

Figure 2: P_0 & T_0 vs. time for transient adiabatic flow in a pipe – closed end

Various steady-state flow conditions through an orifice were analysed in [1]. It was found that the loss model used in RELAP5 did not satisfy energy conservation. A difference in total temperature was found between the orifice in and outlet. The cause of this energy conservation error could not be determined and needs to be resolved with the US NRC.

Transient flow through an orifice was investigated using a pipe geometry as described in Table 1. An orifice with a k-loss equal to 10 was inserted in the middle of the pipe, dividing the pipe into two 5 meter sections. A transient was again initiated by closing a valve at the downstream end of the pipe once steady-state conditions have been reached. Steady-state conditions were reached by using an upstream total temperature and pressure of 15ºC and 8000 kPa respectively. The otal pressure at the downstream end was set to 4000 kPa. For each code the total pressure and temperature at the closed end are compared in Figure 3.

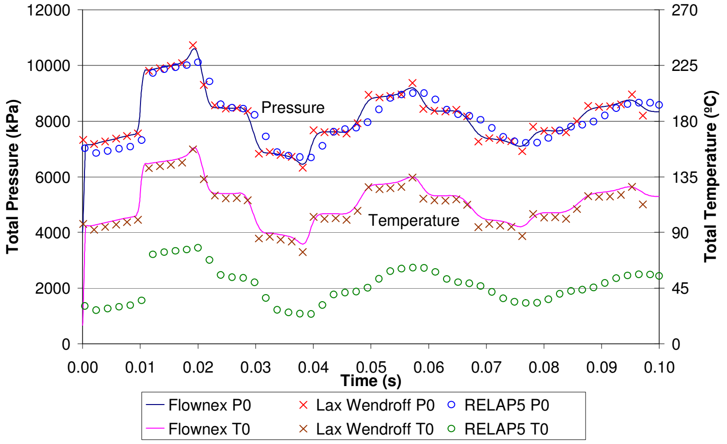

Figure 3: P_0 & T_0 vs. time for transient flow through an orifice – closed end

For steady-flow through a junction one can easily show that conservation of mass, energy and momentum is satisfied by comparison with analytical results. A simple way to test this over a range of conditions is to consider a quasi-steady blow down between three tanks. Figure 4 shows the network used in Flownex. Initially the pressures and temperatures at tanks 1,2 and 3 are fixed to obtain a steady-state solution. The input data for the network is given in Table 2.

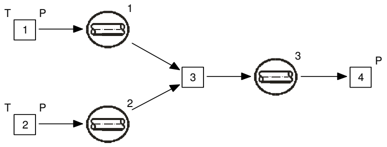

Figure 4: Flownex network for quasi-steady blow down through junction

Geometrical (m)		**Pressures (kPa)**		**Temperatures (°C)**	
Length$_{1,2,3}$	100	P_01	9000	T_01	15
Diameter$_{1,2,3}$	0.065	P_02	9000	T_02	900
Volume $_{\text{Nodes 1,2,4}}$	50	P_04	2500		

Table 2: Input to quasi-steady blow down through junction

This geometry was chosen to approach quasi-steady conditions during the blow down. For this initial solution the results are compared in Table 3. Releasing the fixed pressure condition on the tanks results in a quasi-steady blow down. In Figure 5 the mass flow through each of the pipes is plotted for each code vs. time. During this blow down the tank pressure and temperature results in Flownex was used as boundary conditions to calculate steady-state analytical solutions at regular time intervals.

	P_03 (kPa)	**T_03 (°C)**	**m1**	**m2**	**m3**
Analytical	8251.88	307.04	3.034	1.495	4.529
Flownex	8251.47	307.04	3.035	1.495	4.530
Lax-Wendroff	8252.70	307.04	3.033	1.494	4.527
RELAP5	8121.83	316.03	3.186	1.594	4.780

Table 3: Steady-state initial results for quasi-steady blow down through junction

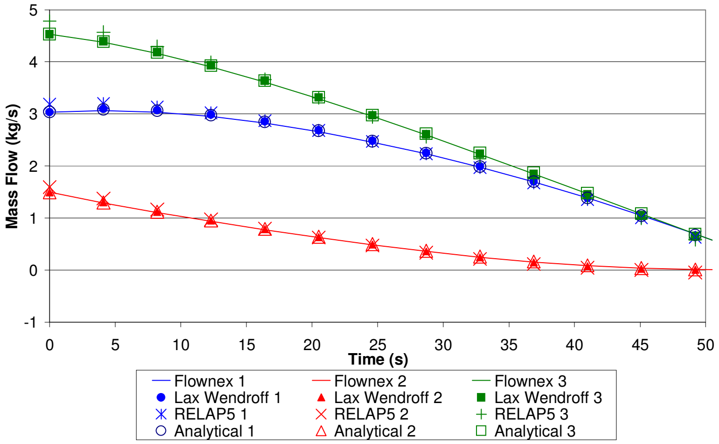

Figure 5: Mass flow vs. time for quasi-steady blow down through junction

For transient flow through a junction the three tanks in Figure 4 were replaced with total pressure boundaries. Input for the steady-state initial condition is given in Table 4.

Geometrical (m)		**Pressures (kPa)**		**Temperatures (°C)**	
Length$_{1,2,3}$	5	P_01	9000	T_01	15
Diameter$_{1,2,3}$	0.065	P_02	9000	T_02	15
		P_04	7000		

Table 4: Input to transient junction network

A summary of the steady-state initial solution is given in Table 5. A transient is initiated by closing a valve downstream of Element 3. Total pressure and temperature vs. time at the junction is given for Flownex and Lax-Wendroff in Figure 6. Transient results obtained with RELAP5 seemed totally unrealistic and was therefore not be presented here.

	$P_0$3 (kPa)	$T_0$3 (ºC)	m1	m2	m3
Analytical	8698.04	15.00	8.6089	8.6089	17.2177
Flownex	8698.04	15.00	8.6089	8.6089	17.2177
Lax-Wendroff	8698.04	15.00	8.6089	8.6089	17.2178
RELAP5	8704.89	15.09	8.5558	8.5558	17.1120

Table 5: Steady-state initial results for transient junction network

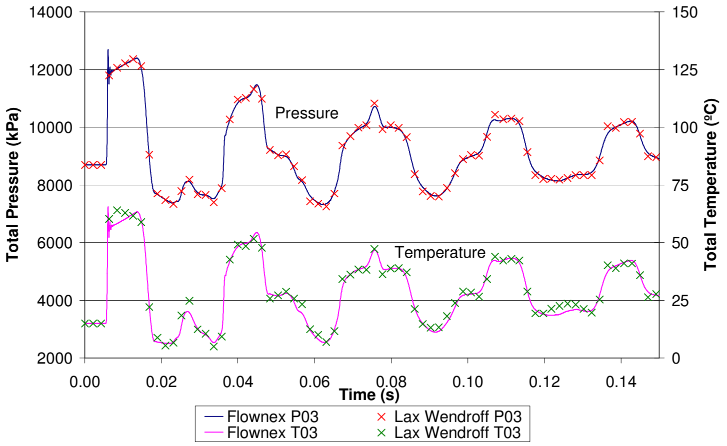

Figure 6: P_0 & T_0 vs. time for transient junction network – Node 3

With the selected fundamental components V&V'd the integration of these components into an arbitrary structured network can now be evaluated. Figure 7 shows the network as it was drawn in Flownex with its associated inputs in Table 6. Mass is circulated through this closed circuit by Element 10. Specifying the pressure at Node 16 fixes the total mass in the system. If mass is conserved for steady flow the flow in Element 8 will be zero. Tanks specified at Nodes 13, 14 and 16 add inertia to the transient response of this network. By specifying the temperature at Node 15 the energy level (temperatures) of the network is determined. If energy is conserved the Helium entering Pipe 10 will have the same total temperature as the specified value of Node 15. The steady-state results for each code are given in Table 7.

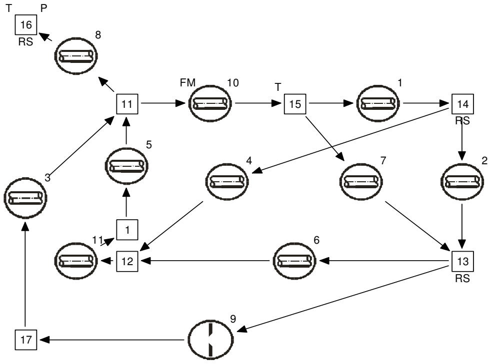

Figure 7: Flownex arbitrary structured network

Geometrical (m)		**Pressures (kPa)**	
Length$_{1,2,3}$	5	P$_0$16	7000
Length$_{4,5}$	15		
Length$_{6,7,8}$	10	**Temperatures (°C)**	
Diameter$_{all}$	0.065	T$_0$15	500
Roughness	0.00003	T$_0$16	500
k-loss$_9$	1	**Mass flow (kg/s)**	
Volume$_{3,4,6}$	10	M10	10
Heat transfer Pipe 2		-10000 (kW)	
Heat transfer Pipe 3		10000 (kW)	

Table 6: Input to arbitrary structured network

(kg/s)	**m1**	**m2**	**m3**	**m4**	**m5**	**m6**	**m7**	**m8**	**m9**
Flownex	5.742	3.822	5.579	1.92	4.421	2.501	4.258	0	5.579
L Wend.	5.743	3.823	5.58	1.919	4.421	2.502	4.258	0	5.579
RELAP5	5.709	3.735	5.695	1.974	4.305	2.331	4.291	0	5.695
(kPa)	**P$_0$11**	**P$_0$12**	**P$_0$13**	**P$_0$14**	**P$_0$15**	**P$_0$16**	**P$_0$17**		
Flownex	7000	7639.06	7745.54	7775.25	8184.54	7000	7539.12		
L Wend.	7000	7638.91	7745.44	7774.96	8184.34	7000	7538.97		
RELAP5	7044.45	7655.94	7770.34	7805.49	8176.72	7000	7571.58		
(°C)	**T$_0$11**	**T$_0$12**	**T$_0$13**	**T$_0$14**	**T$_0$15**	**T$_0$16**	**T$_0$17**		
Flownex	500	365.36	261.99	500	500	500	261.99		
L Wend.	500	365.33	262.02	500	500	500	262.02		
RELAP5	509.26	371.53	261.68	500.6	501.23	500	273.84		

Table 7: Steady-state initial results for arbitrary structured network

A very short pipe, Pipe 11, was added to initiate a transient. At the beginning of the transient the mass flow through this pipe is set to zero. This is equivalent to suddenly closing a valve upstream of Pipe 5. At the same time the pressure specification on Node 16 as well as the temperature specification at Node 15 & 16 was released. This implies that the pressure and temperature at these nodes are solved using mass and energy conservation. Throughout the transient the mass flow through Pipe 10 is kept at 10 kg/s. The total pressure and temperature time response for each code at Node 12 is given in Figure 8. In Figure 9 the mass flow through the orifice element is plotted.

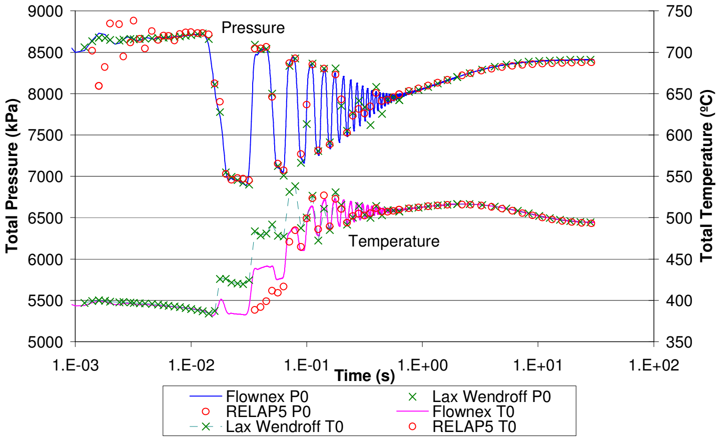

Figure 8: Total pressure and total temperature at Node 12

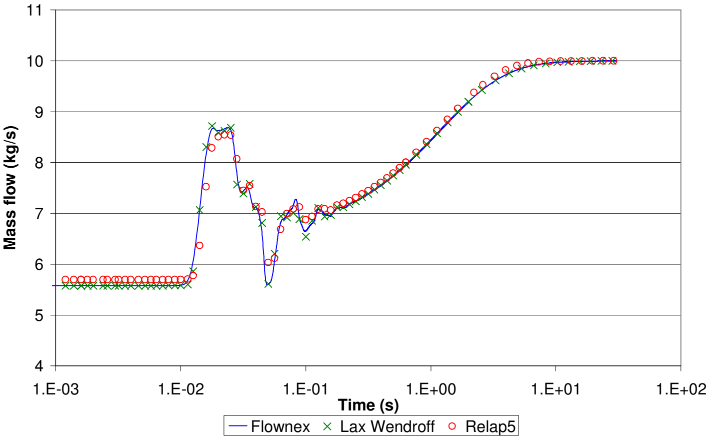

Figure 9: Mass flow through orifice (Element 9)

5. CONCLUSION

For all components in Flownex and Lax-Wendroff compared very well with analytical steady-state results. With RELAP5 some deviations from analytical solutions were found at high Mach numbers (See Table 3 and [1]). It appears that RELAP5 does not satisfy energy conservation when modelling pressure losses through an orifice. This explains the total temperature difference between RELAP5, Flownex and Lax-Wendroff (see Figure 3 and results for Node 11 in Table 7).

For transient flow Flownex compared very well with Lax-Wendroff for evaluated components as well as for an arbitrary structured network. An irregularity in determining the total temperature at some boundaries was found between Flownet and Lax-Wendroff (Figure 2 & Figure 8). This localised effect was considered to have a small or no impact on the rest of the solution. In conclusion: the implementation of individual components considered in this study as well as integration of these components to model pipe networks using Flownex have been validated.

6. REFERENCES

[1] F.BOTHA, “An explicit method for the analysis of transient compressible flow in pipe networks”, *Potchefstroom: PU for CHE. (Thesis – M.Eng.),* 2003. Magister Scientiae (Engineering)

[2] G.P. GREYVENSTEIN, “An implicit method for the analysis of transient flows in pipe networks”, *Int. J. Numer. Mth. Engng.*, 53, 1127-1143 (2002).

[3] W.A. LANDMAN, E. VAN HEERDEN, J.P. VAN RAVENSWAAY AND G.P. GREYVENSTEIN, “Flownet nuclear architecture, implementation, and verification & validation”, *International Congress on Advances in Nuclear Power Plants,* 3298 (ICAPP 2003).

[4] R.V. COETZEE, J. VAN DER MERVE AND J.P. VAN RAVENSWAAY, “Flownex version 6.41 user manual”, *M-Tech Industrial*, Potchefstroom (2003).

[5] WINTERBONE, D.E. AND PEARSON, R.J. 2000. “Theory of engine manifold design”, *London : Professional Engineering Publishing Limited*, 476p.

[6] NATIONAL NUCLEAR REGULATOR, “Licensing guide – Requirements for licensing submission involving computer codes and evaluation models for safety calculations”. LG-1038