Hydraulic matching of an engine cooling system for automotive applications in advanced engineering

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Summary

Due to tight automotive development schedules it's mandatory to estimate coolant flow rates in engine cooling circuit branches early in advanced engineering, to assess specification issued by powertrain and thermal comfort departments. Very basic Flowmaster2 networks can be used in order to spot weaknesses and validate alternatives for engine coolant circuits hydraulic performances and can be expanded to perform crude but cost effective thermal simulation too.

Keywords

engine cooling, Flowmaster2, advanced engineering, simulation

Automotive Engine Cooling system: a challenge

Despite simple physics driving automotive engine cooling system performances the task of design, test and release it is a complex matter. Automotive engine cooling system performances are influenced by many vehicle parameters such as aerodynamics constraints, fashion requirements, vehicle dynamic performances, engine compartment layout and above all powerpack torque, fuel economy and thermal behavior.

To manage efficiently his system an automotive engine cooling engineer has to get back to the basics and focus on three specific topics: heat rejection to engine fluids, which depends upon road conditions and driving pattern, vehicle, engine and gear box usage; cooling air flow, variable according to vehicle speed, aerodynamics, fan size, power and control; engine fluids flow rate, driven mainly by engine speed. But automotive engine cooling engineer is mostly challenged by time. A well known and hardly learned postulate states that the more efforts are spent in advanced engineering, the less problem will be faced afterwards. Unfortunately an industrial project is far from complete and detailed in advanced engineering, while development planning is defined even earlier and time scheduled for system analysis was allocated according barely modifiable milestones. Some sort of balance between simulation model accuracy and reliability has to be found to reduce risks while evaluating engine cooling system performance running multiple analysis (“what if...”), checking and report results, ask for project modification or trade-off performances, all in a shorter and shorter time. Automotive engine cooling engineers are efficiently supported by hydraulic and thermal network simulators such as Flowmaster2 that let a skilled user set up a basic engine cooling model in a matter of days, if not hours, and modify quickly parameters: but a tool is nothing without a work plan and philosophy that optimize time and efforts.

“Entia non sunt moltiplicanda praeter necessitatem”

All industrially manifactured objects share common properties in advanced engineering, for example their shape is not frozen yet and performance requirements are discussed and re-issued many times. For vehicle design purposes this means you cannot trust cooling air flow predictions for long while vehicle and powerpack matching has to be calibrated many times. So missing both reliable heat rejection to engine fluids and cooling capability estimations you can either work with a multiple choice simulation network and risk “spaghetti code effect” or concentrate your efforts on steady input data and build up simple but quickly upgradable simulation network to include all new references. If clear understanding of project design and release process is team-wide shared the second option is far better then the first one.

While a vehicle project can be recast many time in advanced engineering engines are not modified on a short term period. Notable examples are Rolls Royce Merlin or Pratt and Whitney Double Wasp aircraft powerpacks, not to the mention the legendary General Electric J79 whose life has been spanning two combat plane generations. Moreover component improvement or layout shift usually does not affect engine fluid jackets and channels design, so automotive cooling engineers can save time studying and assessing coolant or oil flow rate with a Flowmaster2 network before and later on investigate cooling air flow rate adding new elements.

But even a very basic simulation model focused on engine cooling distribution studies has to be bone-stripped in order to be time – effective, so let’s focus on engine cooling system functions. Engine coolant pump(s), either mechanically or electrically driven, moves coolant heated by engine combustion and frictions outside the engine block to a series of components whose purposes are:

1) radiator: transfers heat from coolant to cooling air, discharged underbelly through the engine compartment

2) cabin heater: transfers heat from coolant to air and then to passenger compartment for thermal comfort

3) oil coolers: transfers heat from engine or gear box oil to coolant

4) hot bottle: removes vapour and air from coolant, pressurize the engine cooling circuit and let customer refill it

5) thermostatic valve(s): mechanically or electrically operated is closed or open according to coolant temperature and engine load or speed, thus modifying coolant flow rate in each cooling circuit branch

6) pipes: links engine cooling components each other and to the engine, so coolant flows through them

An engine cooling circuit operates in two distinct modes, “cold” and “hot”. In “cold” mode thermostatic valve(s) is closed due to low coolant temperatures, so there is no coolant flow through the radiator and no heat transfer is provided by this component. It’s supposed that ambient temperature, engine load and speed are low, so engine cooling system engineers are concerned about passenger compartment and engine warm up: primary target is achieving correct cabin heater coolant flow rate target, secondary target is feeding the hot bottle to clean the circuit, but you have not to exceed to guarantee a quick drop of engine friction resistance and thus a better fuel economy. In “hot” mode ambient temperature is likely high, as engine load and speed: the engine cooling system has to work at full capacity in order to keep thermally safe the engine block, engine and gear box oil, so oil coolers and radiator coolant flow rates target has to be met according to powerpack specs.

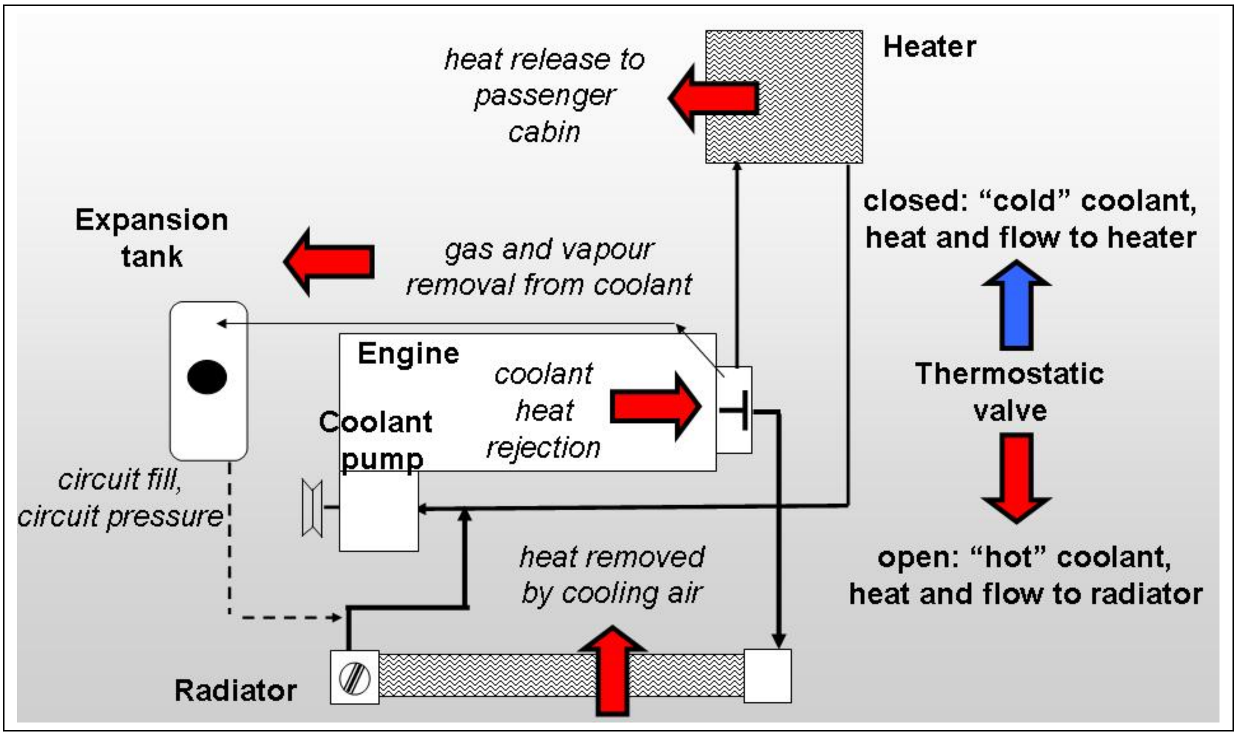

Figure 1. Basic functions of an automotive engine cooling system

As you can see there are minor tasks only to accomplish when the thermostatic valve is partially open. This fact can be used to simplify an engine coolant flow rate - oriented Flowmaster2 network and still keep it reliable.

"Kiss it – keep it simple, son "

In order to create and run a simple but effective engine coolant network suited to study coolant flow distribution in advanced engineering you have to strip down it. If you are supported by an excellent test bench team, reliable component supplier and share constantly information with powertrain and HVAC departments four basic assumptions can lead you to perform this task.

Assumption (1) You are sizing engine cooling system for capacity, so there is no need to perform either transient analysis or care too much about coolant and component thermal inertia properties: a dozen steady state, fixed engine speed analysis with thermostatic valve closed and open are what you need

Assumption (2) Pipe routing is usually undefined or when available usually does not last for long, so it's useless setting up fine modelling of bend – straight – elbow patterns: approximate each branch with a pipe to take in account friction losses and a generic loss component to include accidental pressure drops due to deviations.

Assumption (3) Engine compartment layout, car fashion and radiator – cabin heater suppliers are conjectural or unknown, so there is no need to create an elaborate cooling air flow path: a simple heat exchangers, air flow and air pressure sources to supply it are enough

Such assumptions let skilled cooling engineers set up and run a simulation model quickly, even in a matter of minutes if a pre-set template is available and ready to be filled with inputs. Reliability is only fair, but is good enough to drive advanced engineering: statistical evidence shows that even without test data to tune Flowmaster2 models a simplified coolant network estimates coolant flow rates with a typical error of 15%. Best results occur for radiator branch when thermostatic valve is open, worst results are found for hot bottle with thermostatic valve is closed. It seems that there is no engine type related error dependence – large, small, diesel, gasoline powerpacks performs nearly the same way – while it appears that low engine speed provides the worst results. KISS "cold" models run with thermostatic valve closed are used to discuss with powertrain and thermal comfort departments target achievement of coolant flow rates for cabin heater, oil coolers, hot bottles and provide input data for subsequent, more refined analysis.

One step beyond: "hot" and "thermal" KISS models

KISS "hot" models dealing with an engine coolant circuit that performs with thermostatic valve open are the most interesting ones for automotive cooling engineers. They allow you to check compliance with powertrain requirements about temperature decrease across main radiator, let you select heat exchangers whose coolant pressure drop is compatible with this target. But paying a modest price in complexity both "cold" and "hot" models can be upgraded in order to investigate thermal issues, simulating simple vehicle drive patterns in "nearly steady-state" conditions. This involves identifying and inserting in the model cooling air flow rate for a specific vehicle speed, applying radiator and cabin heater thermal performance maps, add a lumped-mass and an heat source to engine block sub-model and run simulations keeping speeds, ambient temperature, engine heat rejection constant for a specified amount of time or mileage. By tuning this models on previous vehicle-level testing you can get preliminary warm-up results in cold environment for passenger thermal comfort estimation or fuel economy improvement purposes, while in hot environment you can predict maximum coolant temperature for high vehicle speed or set cooling air flow rates target to be assessed and discussed with aerodynamic department or engine cooling module suppliers according to vehicle manufacturer test standards.

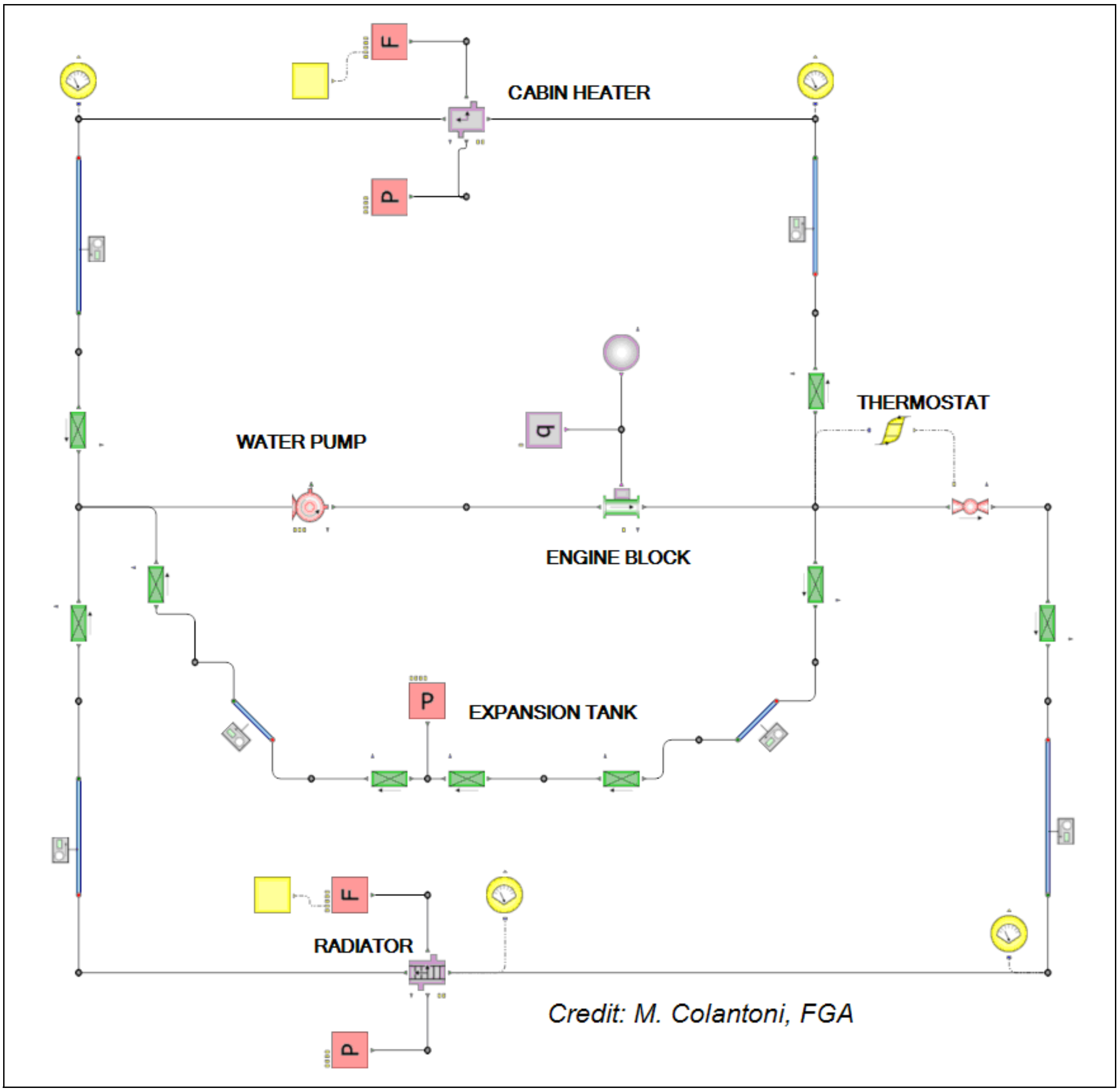

Figure 2. "KISS thermal" Flowmaster model including basic characteristic of an automotive engine cooling system: coolant branches, engine heat rejection and engine lumped-mass thermal capacity, heat exchangers, temperature controlled thermostatic valve, cooling air flow generators for radiator and cabin heater

Despite apparently bare boned “KISS thermal” Flowmaster2 models results are reliable enough. Figure 3 shows a comparison of one of first simulation run in cold environment: thermostatic valve opening occurs nearly at the same moment both for calculation and testing and correlation for cabin heater inlet temperature is fair. Differences are larger for radiator inlet temperature, but you have to take in account that some thermostatic valve leakage occurs on vehicle tested, while the simulation network does not model this effect. Experimental and calculation comparison shows that knowledge of thermostatic valve behaviour and engine thermal inertia are the most relevant topics to be investigated and improved.

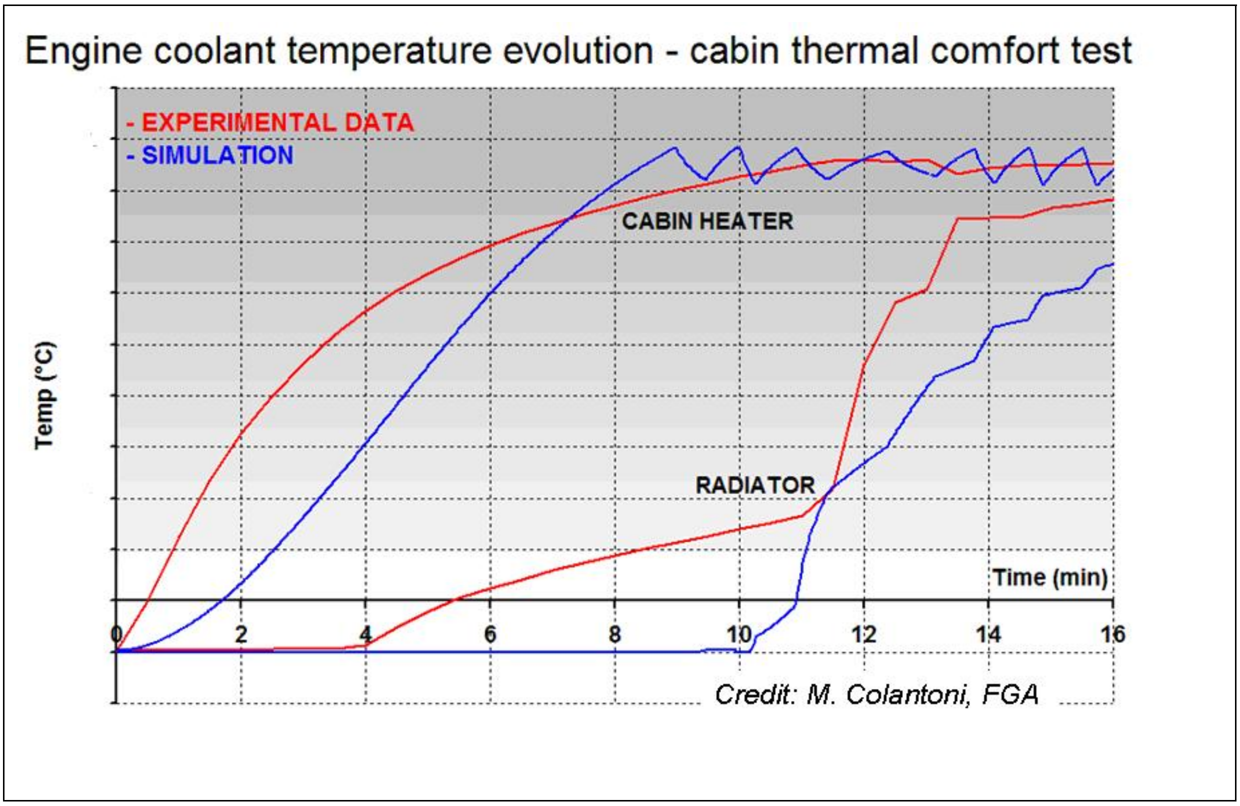

Figure 3. “KISS thermal”Flowmaster simulation model results compared with test data

Final step: KISS “transient” models for cooling field tests

The most advanced and promising usage of Flowmaster2 for automotive cooling topics is investigation of transient engine thermal behaviour while running fuel economy driving patterns. Qualitative relationship between quick engine warm up and reduced need for fuel is well known, but it’s hard to study proficiently even using complex simulation models. On the contrary even KISS Flowmaster2 networks can be used successfully to support investigations of cooling field test results, usually fast laps on tracks or hill / mountain runs, and can even anticipate coolant temperatures if additional elements are embedded.

Such implementations include a very simple cooling air flow network that evaluates air flow rates through radiators according to vehicle and fan speeds, a controlled coolant pump and variable heat rejection to coolant. To feed these network elements a proprietary Simulink based tool was developed: it predicts instantaneous vehicle and engine speed according to gear usage, available engine torque, vehicle aerodynamic drag and rolling resistance and a basic grip-traction-cornering speed relationship. Both open or closed loop driving patterns can be evaluated and each pattern is split in smaller segments characterized by length, bend radius, grade.

One of the first investigations performed is an uphill ride 3.2 km long with a shorter straight and nearly flat first section and a longer 8% grade second section including a dozen of hairpins, performed in 225 seconds. Simulation results here refers to model assessments, with averaged vehicle speed, engine speed and engine heat rejection to coolant in each section, but the model performs smoothly and quickly using less coarse input profiles. Thermostatic valve opening and fan activation occurs according to the specifications and coolant temperature rise according to correct radiator heat exchange. Final fine tuning model studies are underway.

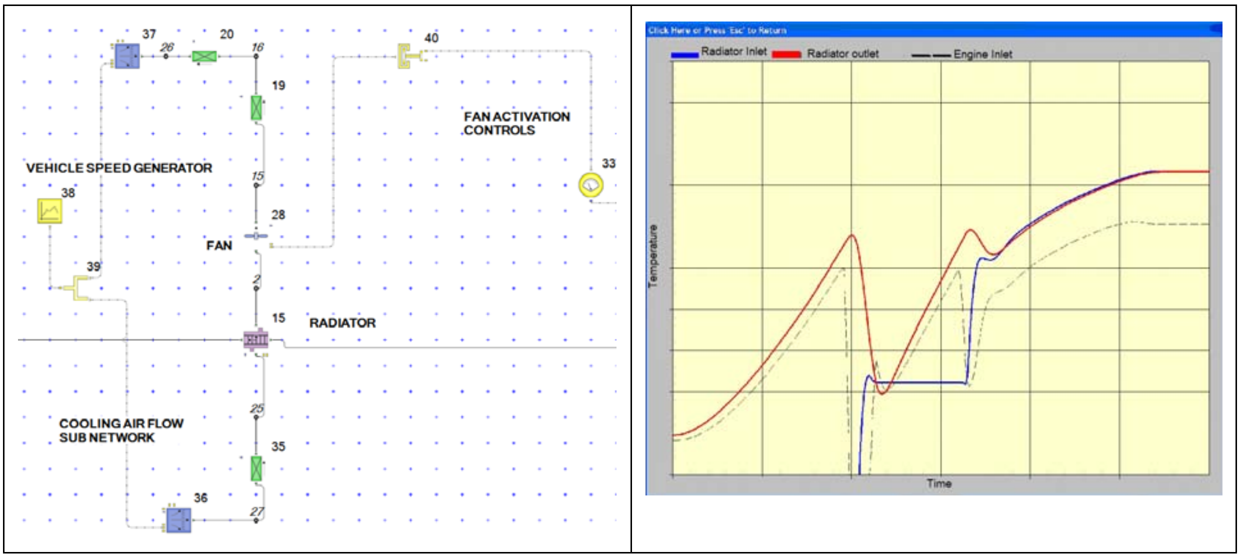

Figure 4. Final evolution step of KISS Flowmaster models is a transient joint simulation of both cooling air and coolant flow rate that includes a temperature controlled fan and a simple air flow sub network with a "overall" vehicle system resistance. On the right you can find engine outlet (red), engine inlet (black, dashed) and radiator inlet (blue) temperature evolution: partial thermostatic valve opening occurs briefly about 100 sec of simulated time and full opening around 165 sec. Beyond that point coolant temperature increases again until fan is engaged, so just before hill summit coolant temperature stabilize.

Conclusions

Hydraulic matching of an automotive engine cooling system performed by simple Flowmaster2 models can both save time in advanced engineering and provide an excellent base to perform later on thermal sizing analysis too - steady state and transient – simply adding relevant component or sub-networks.

Successful achievement of this tasks is not easy anyway: it requires engineering skill and expertise, a good design team relationships, a clear comprehension of project mission and targets, reliable input data. Near future development of "KISS" engine cooling thermal transient models capabilities could include investigation of different customer vehicle usage effects, early development of pumps and valves control programs on real-world driving patterns, and integration or co-simulation of simple vehicle dynamics in or with Flowmaster2

" Things should be made as simple as possible… but no simpler " (A. Einstein)

References

[1] Cavallino, Morra, Piccone. "Powerpack applications to vehicle. Module A: Engine Cooling System". Politecnico di Torino, Turin – Italy. Automotive Engineering School, 1996

[2] Idelchick. "Handbook of hydraulic resistance", Hemisfere Pubishing Co, 1986

[3] Burke, Haus "Vehicle thermal systems modeling using Flowmaster2". SAE Paper 2001-01-1692, 2001

[4] Damodaran, Rahman "Front end cooling airflow. Performance prediction using vehicle system resistance" SAE Paper 2003-01-0273, 2003