Adjustment of a 1d engine cooling system model to wind tunnel test results

Engine Cooling

Steyr, 30 june 2005

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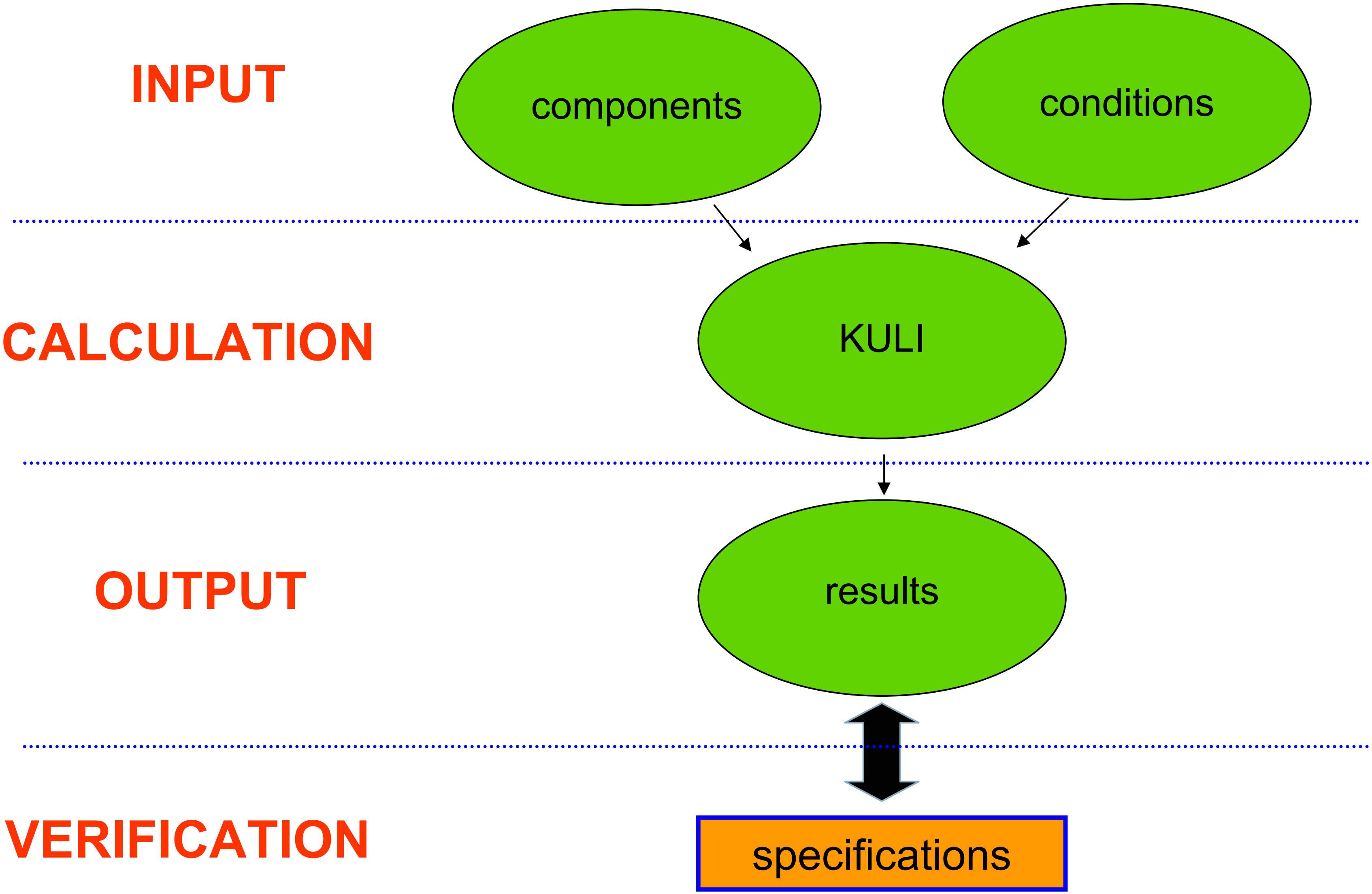
Thermal simulation

Calculation process



Calculation process

The aim of a thermal performance calculation is to estimate the values of the required characteristic parameters (results) in given vehicle working points (conditions) and to verify if they comply with the specifications

what's necessary to know:

1. customer's data to be used as an input for the thermal performances calculation
2. maximum allowed values for the characteristic parameters
3. thermal characteristics of every component used in the engine cooling system
4. effect of the vehicle on the air flow through the heat exchangers

It will be assumed that points 1, 2 and 3 are known and a description of the method to evaluate the effect of the vehicle on the cooling air flow (point 4) will be presented.

Calculation process

TARGET

estimate the thermal performances of an engine cooling system once the performances of each **component** and the working conditions are known

What is usually unknown

the **effect of the vehicle** on the cooling air flow rate (vehicle speed effect, drop in pressure through the engine bay) is usually unknown

effect taken into consideration in **wind tunnel test**

Model adjustment

ADJUSTING THE MODEL

obtaining a cooling model that matches wind tunnel test results through the two following steps:

1. adjusting a 1d engine cooling system model to a **single wind tunnel test point**

2. adjusting a 1d engine cooling system model to **all the wind tunnel test points** at the same time

Step 2 allows the use of a single model to predict the thermal performances of the engine cooling system in several working points

Model adjustment

VEHICLE EFFECTS

The effect of the vehicle on the cooling air flow through the engine cooling module can be reduced to two elementary effects:

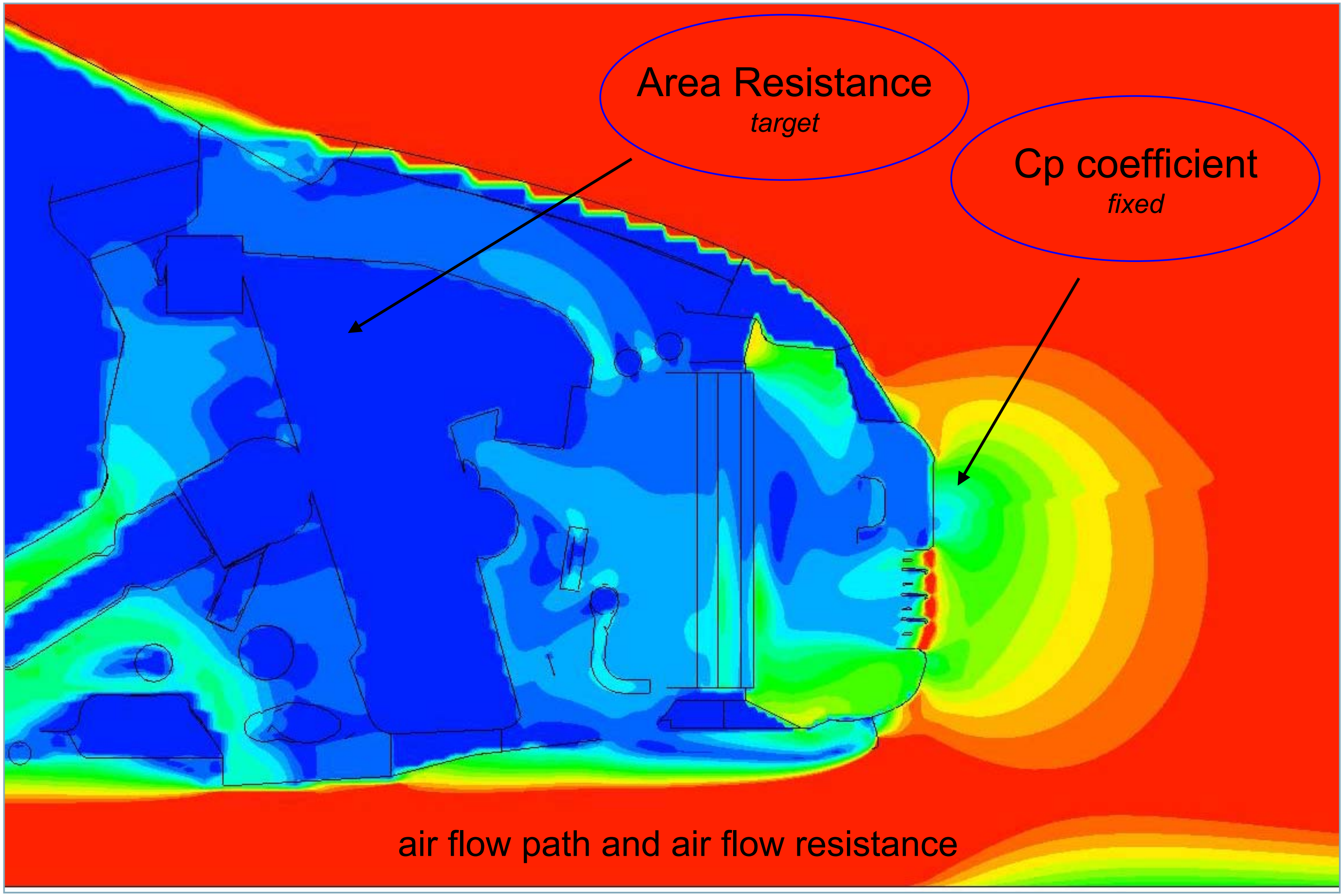
- ram effect
- vehicle pressure drop effect

☞ *it is important to have a calculation model that can predict the air flow and the thermal performance*

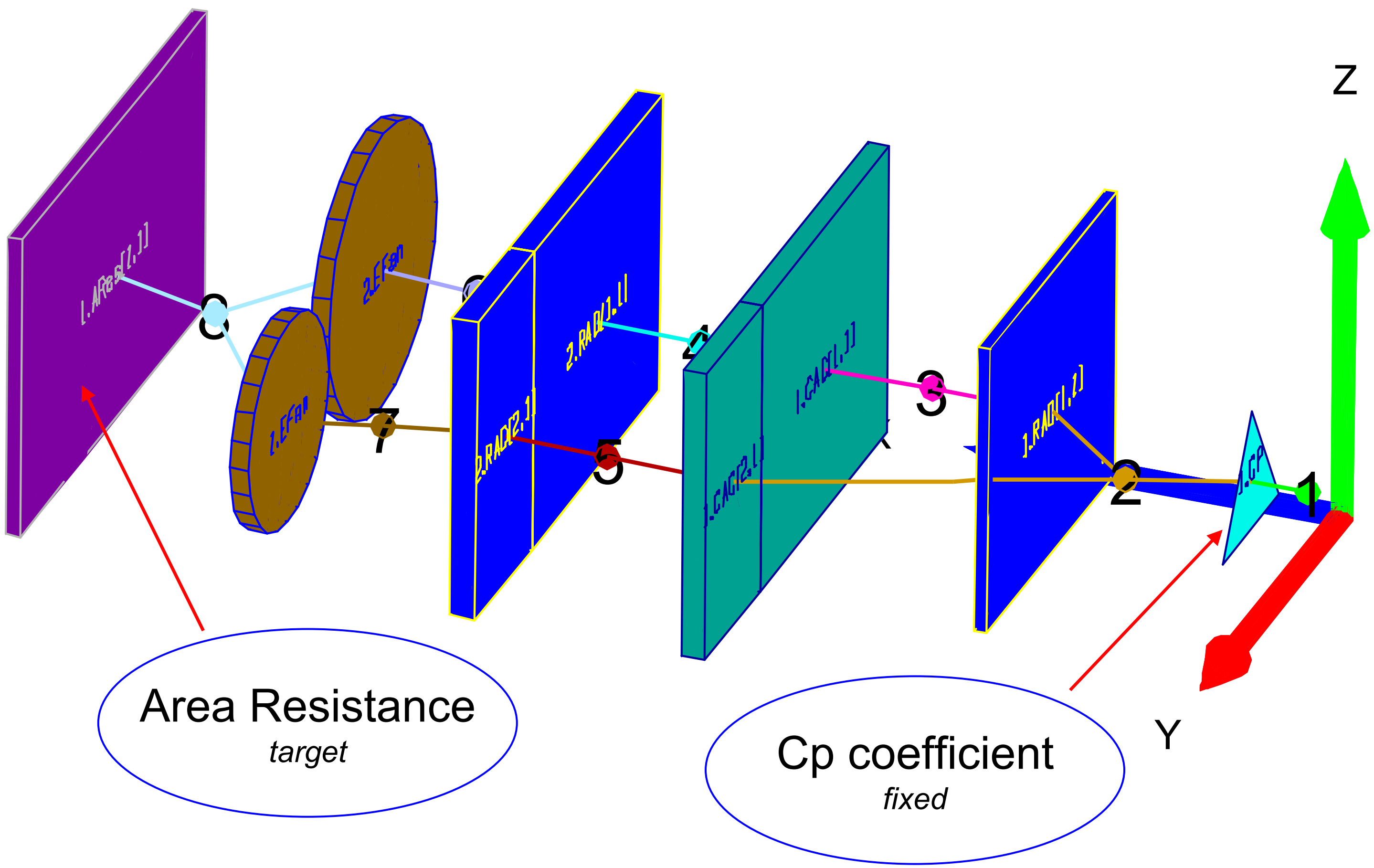
☞ *it is not essential to know how to **split** the contribution to the air flow between ram effect and vehicle pressure drop effect*

- *ram air effect is set to a "mean" value (e.g. cp = 0.9)*
- *vehicle pressure drop effect is assigned in order to have the same (thermal equivalent) air flow through the engine cooling module as in reality (i.e. to comply with the wind tunnel test results)*

Model adjustment

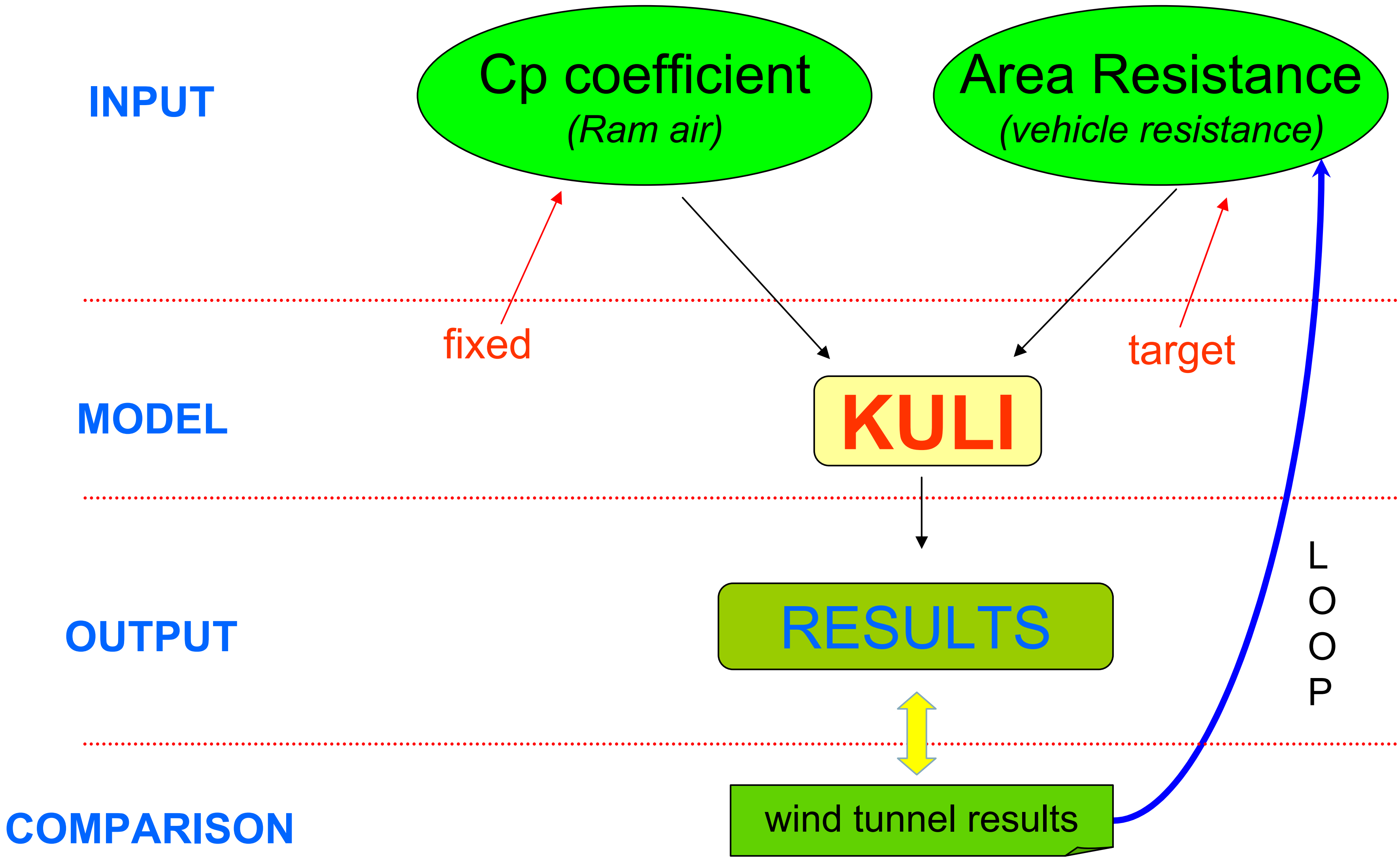


Model adjustment



air flow path and air flow resistance in the engine cooling model to be calibrated

Model adjustment



Model adjustment

MODEL: CALIBRATION: ➔ ➔ ➔ **RAM AIR EFFECT: <u>FIXED</u>**

➔ ➔ ➔ **VEHICLE PRESSURE DROP: <u>CALIBRATION</u>**

COMPARISON: ➔ ➔ ➔ **WIND TUNNEL RESULTS**

Model adjustment

ADJUSTING THE MODEL TO A SINGLE WIND TUNNEL TEST POINT

Defining the vehicle air flow resistance to match with a single wind tunnel test point

Let's consider a calculation model representing the engine cooling system tested in the wind tunnel (i.e. same components, same conditions).

If the vehicle air flow resistance is defined by means of an equation like the one below:

Model adjustment

$$\Delta p = a \cdot u^2$$

at given air temperature and pressure conditions:

$$T = T_0$$

$$\mathrm{p} = \mathrm{p}_0$$

where:

T = reference temperature to define the vehicle resistance

p = reference pressure to define the vehicle resistance

u = air velocity through the resistance

Δp = air pressure drop through the resistance

and for given dimensions of the resistance:

$$\mathrm{W} = \mathrm{W}_0$$

$$\mathrm{H} = \mathrm{H}_0$$

$$\mathrm{D} = \mathrm{D}_0$$

Model adjustment

It is enough to find the value to assign to the parameter **a** in order to obtain the same value of the chosen characteristic parameter as measured in the wind tunnel, to adjust the cooling system model to that single point.

Let's consider, as an example, this wind tunnel test point:

car speed [km/h]	ambient Temp [°C]	radiator coolant flow [kg/s]	radiator coolant entry Temp [°C]	radiator heat rejection [kW]
31	19.8	2.531	111.9	45.7

and let's choose the **radiator heat rejection [kW]** as the characteristic parameter to adjust the model to the experimental results.

With these reference conditions for the **area resistance**:
T = 20 °C
p = 1013 hPa
and:
W = 650 mm
H = 415 mm
D = 20 mm
the parameter **a** has to be defined.

Model adjustment

With the Kuli "optimization target" function, it is possible to find, within a specified range, the value to assign to the parameter **a** (**optimization parameter**), to obtain the target value for the heat rejection (**optimization target**).

In this example:

- the optimization target is: radiator heat rejection [kW] = 45.7
- the optimization parameter is **a**
- the variation range for the optimization parameter must comply with: 30 < **a** < 40

KULI gives as a result:
a = 34.056

The 1d calculation model, with the air flow resistance defined above and with the calculated value of the optimization parameter, is now adjusted to the single wind tunnel test point considered

Model adjustment

This operation can be done for all the wind tunnel test points:

*different air flow resistances will be found for each point (optimization parameter **a** will have different values for each point)*

This means that the model can be adjusted to each single wind tunnel test point but is not yet adjusted to all the wind tunnel test points at the same time

Each air flow resistance thus obtained is actually valid only to define the air pressure drop which corresponds to the specific calculated value of the air velocity through the resistance itself at the calculated temperature and pressure at the air flow resistance entry.

Model adjustment

When it is necessary to verify the thermal performances of an engine cooling system, it is necessary to have a single air flow resistance which is valid for whatever test point.

That means that it is necessary to have a **single air flow resistance** that can provide, for whatever air flow rate through the air flow resistance itself and for whatever air inlet temperature and pressure, the corresponding pressure drop.

next step

To achieve this target it is necessary to adjust the 1d engine cooling system model to **all** the wind tunnel test points at the same time

Model adjustment

ADJUSTING THE MODEL TO ALL THE WIND TUNNEL TEST POINTS AT THE SAME TIME

Finding a relationship between the pressure drop and the flow rate, valid for whatever air temperature and pressure, that complies with all the wind tunnel test points

This can be done with an analysis of the air flow resistance working points found when adjusting the 1d cooling system model to each single wind tunnel test point.

Model adjustment

This table shows, for each wind tunnel test point considered, the value of the optimization parameter a to adjust the model to that point

car speed [km/h]	ambient Temp [°C]	radiator coolant entry Temp [°C]	radiator coolant flow [kg/s]	radiator heat rejection [kW]	Opt param a	entry Temp [°C]	entry pressure [hPa]	pressure difference [Pa]	Mass Flow rate [kg/s]
31	19.8	111.9	2.531	45.7	34.056	98.4	1015	211	0.719
49	20.8	112.2	2.172	53.6	26.295	94.9	1015	231	0.859
65	12.5	103.3	2.911	57.3	28.083	86.1	1016	297	0.955
80	12.2	93	2.316	58.4	23.392	72.3	1016	340	1.142
219	12.2	89.1	2.978	87.9	34.474	59.8	1029	1608	2.097

Model adjustment

For each wind tunnel test point the **mass flow rate** and the corresponding **pressure drop** for the air flow resistance are known:

this is not yet enough to define a relationship between pressure drop and flow rate because to specify an air flow resistance completely it is necessary to know:

- ✓ the pressure drop and the flow rate
- ✓ the geometrical dimension of the resistance
- ✓ the reference temperature and pressure

now the reference temperature and pressure are different for each wind tunnel test point …

… the reference temperature and pressure for an air flow resistance matching all the wind tunnel test points are <u>not yet defined</u>

Model adjustment

To overcome this problem it is possible to calculate the values that the pressure drop and the flow rate would have in given temperature and pressure conditions (that will be chosen equal for all the wind tunnel test points)

Let's assume, as reference conditions:

T_0 = 20 °C

p_0 = 1013 hPa

The values that the pressure drop and the mass flow rate would have in these new reference conditions (T_0, p_0) can be calculated with the hypothesis that the Reynolds number (Re) and the friction factor (f) are the same in the reference conditions (Re_0, f_0) and in the test conditions (Re_t, f_t).

Model adjustment

To calculate the air mass flow rate, let:

$Re_0 = Re_t$

this is equivalent to: $$\frac{\rho_0 \cdot u_0 \cdot d}{\mu_0} = \frac{\rho_t \cdot u_t \cdot d}{\mu_t}$$

As the hydraulic diameter and the cross section are the same in both conditions it is also:

$$Q_{m0} = Q_{mt} \cdot \frac{\mu_0}{\mu_t}$$

and then, by considering the way the air dynamic viscosity changes with the temperature:

$$Q_{m0} = Q_{mt} \cdot \left(0.1781 + \frac{240.92}{273.15 + T_t} \right)$$

Model adjustment

To calculate the pressure drop, let:

$f_0 = f_t$

this is equivalent to:

$$\frac{\Delta p_0}{\frac{1}{2}\cdot\rho_0\cdot u_0^2} = \frac{\Delta p_t}{\frac{1}{2}\cdot\rho_t\cdot u_t^2}$$

that can be written, being $Re_0 = Re_t$, as:

$$\Delta p_0 = \Delta p_t \cdot \frac{\rho_0}{\rho_t}\cdot\left(\frac{\rho_t}{\rho_0}\cdot\frac{\mu_0}{\mu_t}\right)^2$$

and then, by considering the way the air dynamic viscosity changes with the temperature:

$$\Delta p_0 = \Delta p_t \cdot \frac{\rho_t}{\rho_0}\cdot\left(0.1781 + \frac{240.92}{273.15 + T_t}\right)^2$$

or as:

$$\Delta p_0 = \Delta p_t \cdot \frac{p_t}{p_0}\cdot\frac{T_0 + 273.15}{T_t + 273.15}\cdot\left(0.1781 + \frac{240.92}{273.15 + T_t}\right)^2$$

Model adjustment

The formulae thus obtained allow the calculation of the air mass flow rate and the air pressure drop at the air flow resistance in the given temperature and pressure reference conditions (20 °C, 1013 hPa) for all the wind tunnel test points considered.

The table to define the Area Resistance becomes then:

entry Temp [°C]	entry pressure [hPa]	pressure drop [Pa]	Mass Flow rate [kg/s]
20	1013	114	0.595
20	1013	128	0.715
20	1013	175	0.810
20	1013	222	1.000
20	1013	1169	1.891

Model adjustment

It is now possible to define an air flow resistance which establishes the relationship between air mass flow rate and pressure drop, in the specified temperature and pressure conditions (20 °C, 1013 hPa).

As a verification, the air flow resistance just defined has been used in the engine cooling system model to recalculate the radiator heat rejection in all the wind tunnel test points:

the same values of radiator heat rejection as measured in the wind tunnel have been found

☺

the 1d engine cooling system model is now adjusted to all the wind tunnel test points at the same time

Model adjustment

Comparison Kuli results versus wind tunnel measurements

Car speed [km/h] measured	ambient Temp [°C] measured	radiator coolant entry Temp [°C] measured	radiator coolant flow [kg/s] measured	radiator heat rejection [kW] measured	**Opt param a** calculated	Air mass Flow rate [kg/s] calculated	radiator heat rejection [kW] calculated
31	19.8	111.9	2.531	45.7	34.056	0.719	45.7
49	20.8	112.2	2.172	53.6	26.295	0.859	53.6
65	12.5	103.3	2.911	57.3	28.083	0.955	57.3
80	12.2	93	2.316	58.4	23.392	1.142	58.4
219	12.2	89.1	2.978	87.9	34.474	2.097	87.9

Model adjustment

CONCLUSION

A 1d engine cooling system model, adjusted to several wind tunnel test points at the same time, can be used to estimate the performances of a system in whatever vehicle working point within the range of wind tunnel test points considered and it can thus be useful in verifying the thermal performances of an engine cooling system with respect to the customer's specifications.

Advantage

The same model can be used to calculate the engine cooling system whatever the vehicle speed is

Remark

If the module configuration changes …

… the Area Resistance could change too!!!

Contact

THANK YOU FOR YOUR ATTENTION

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