1-D Underhood Airflow Model and KULI Application

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Ying Tang
John R. Savage
Valeo Engine Cooling

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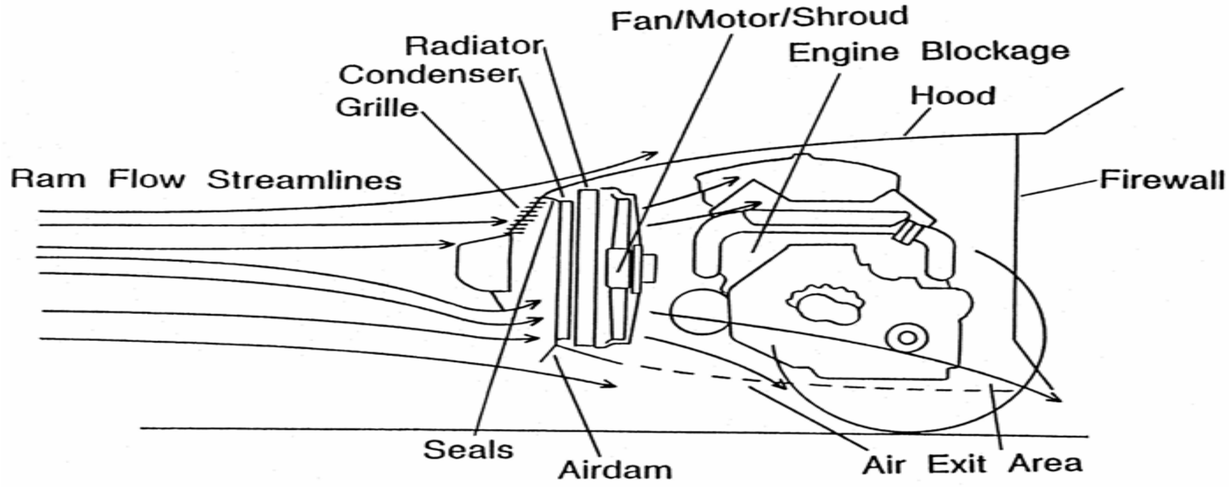
Introduction

In this presentation, we will discuss the following issues:

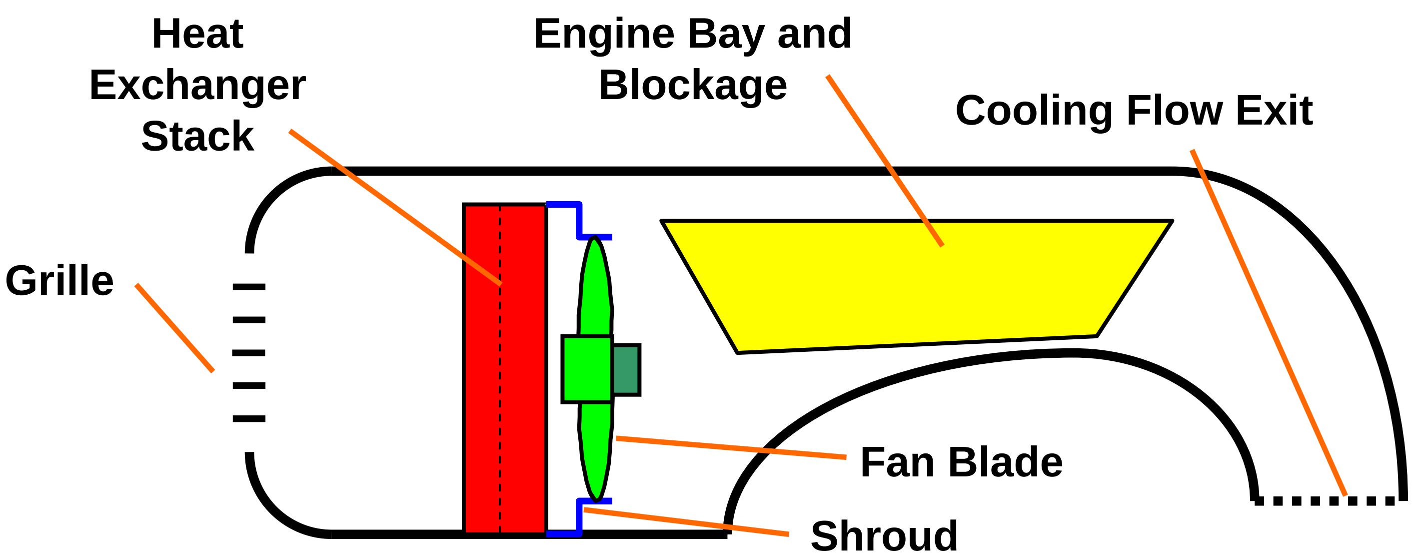
- 1-D underhood airflow model and its indications
- Some commonly used description for the underhood characters
- KULI 1-D simulation model and its application example
- Discussions and comments



Simple 1-D Model Assumptions

To establish a 1-D underhood airflow model, a few assumptions will be needed, such as

- Incompressible flow
- Isothermal flow
- Lumped parameter model for pressure loses
- Fully covered fan shroud



Mathematical Expression

- Two basic physical laws to apply the underhood airflow:
  - Conservation of mass, in the case of incompressible flow, the conservation of volumetrical flow rate.
  - Conservation of energy, in this case, the Bernoulli equation with lumped parameter pressure drop model

- The mathematical expression can be listed as:

$$\Delta P_{fan} = \Delta P_{hex} + \Delta P_{bay} - \Delta P_{cp} - \Delta P_{ex-contr}$$

- The subscripts stand for

  fan = Fan assembly

  hex = Heater exchangers, including condenser, radiator and CAC and Air to oil coolers

  bay = Engine bay

  Cp = Inlet Cp and Outlet Cp

  ex-contr = Airflow in and out vehicle underhood expansion and contraction

Mathematical Expression- cont.

- **Details for mathematical expression :**
  - A. **Terms are related with vehicle speed.**

$$\Delta P_{Cp} = \frac{1}{2}(Cp_{inlet} - Cp_{exit})\rho U_V^2 \qquad \Delta P_{ex-contr} = \frac{1}{2}(\alpha_{inlet}^2 - \alpha_{outlet}^2)\rho U_V^2$$

  - B. **Terms are related with radiator face velocity (HEXs face Velocity).**

$$\Delta P_{fan} = \frac{1}{2}(\beta^2 k_{fan} - k_{shroud})\rho U_r^2 \qquad \Delta P_{hex} = \frac{1}{2}k_{hex}\rho U_r^2$$

β = Radiator surface area/Fan free flow area

  - C. **Terms are related with vehicle speed and radiator face velocity (implicated).**

$$\Delta P_{bay} = \frac{1}{2}k_{bay}(U_r, U_V)\rho U_V^2$$

➔ **A’s terms may be vehicle depended alone and B’s terms may be impacted by engine cooling module only.**

Mathematical Expression- cont.

- **Detailed discussions for k:**

  A. **k for heat exchangers**

  Based on Kays & London's [1] pressure drop expression for an compact heat exchanger. With isothermal and incompressible flow assumptions, the above equation can be simplified as

$$\frac{\Delta P_{hex}}{\frac{1}{2}\rho U_r^2} = [(k_c + k_e) + f\frac{A}{A_c}] = \left(k_c + k_e\right) + \frac{A}{A_c}\frac{const}{\mathrm{Re}^a} = const_1 + \frac{const_2}{U_r^a}$$

$$k_{hex} = const_1 + \frac{const_2}{U_r^a} = a_{hex} + \frac{b_{hex}}{U_r^a}$$

Mathematical Expression- cont.

- **Detailed discussions for k:**
  - B. **k for fan system assembly**

    Typical non-dimensional pressure difference expression may be expressed as

$$\frac{\Delta P_{fan}}{\frac{1}{2}\rho U_{fan}^{2}} = \left(k'_0 + \frac{k'_{-1}}{U_{fan}} + \frac{k'_{-2}}{U_{fan}^{2}} + \frac{k'_{-3}}{U_{fan}^{3}} + \cdots \right)$$

➔ **So k for an fan may be simplified as**

$$\frac{(-k_{shroud} + \beta^2 k_{fan})}{\beta^2} = \left(k'_0 + \frac{k'_{-1}}{U_{fan}} + \frac{k'_{-2}}{U_{fan}^{2}} + \frac{k'_{-3}}{U_{fan}^{3}} + \cdots \right)$$

  - C. **k for other terms may take as constants for simplified propose**

Mathematical Expression- cont.

- **Discussions of velocity ratio, ε expression:**
  1. **If only using the zero order expression for k of fan system assemble and heat exchanger,**

$$k_{hex} = a_{hex} \qquad -k_{shroud} + \beta^2 k_{fan} = \beta^2 k'_0 = \beta^2 a_{fan}$$

➔ **Then, the velocity ratio expression can be written as**

$$\varepsilon = \frac{U_r}{U_V} = \sqrt{\frac{(Cp_{inlet} - Cp_{outlet}) + (\alpha^2_{inlet} - \alpha^2_{outlet}) - k_{bay}}{a_{hex} - \beta^2 a_{fan}}}$$

Mathematical Expression- cont.

- **Discussions of velocity ratio, ε expression:**
  2. **If only using the first order expression for k of fan system assembly and heat exchanger,**

$$k_{hex} = a_{hex} + \frac{b_{hex}}{U_r}$$

$$-k_{shroud} + \beta^2 k_{fan} = \beta^2 (k_0' + \frac{k_{-1}'}{\beta U_r}) = \beta^2 a_{fan} + \beta \frac{b_{fan}}{U_r}$$

➔ **Then, the velocity ratio expression can be written as**

$$(a_{hex} - \beta^2 a_{fan})\varepsilon^2 + (b_{hex} - \beta b_{fan})\frac{\varepsilon}{U_V} - [(Cp_{inlet} - Cp_{outlet}) + (\alpha_{inlet}^2 - \alpha_{outlet}^2) - k_{bay}] = 0$$

Mathematical Expression- cont.

- **Discussions of velocity ratio, ε expression:**
  - ➔ **Then, In the very high vehicle speed situation, the approximated form of solution can be expressed as**

$$\varepsilon = \frac{U_r}{U_V} \approx const_0$$

  - ➔ **And in the general case, the solution can be expressed as**

$$\varepsilon = \frac{U_r}{U_V} = -\frac{Const_1}{U_V} + const_2 \left(1 - \frac{const_3}{U_V^2}\right)^{\frac{1}{2}}$$

Mathematical Expression- cont.

- ## Graphical expression for velocity ratio, ε:

  To present velocity ratio ε vs. vehicle speed U_V in a chart, with high ends will be closed to the approximated expressions as we discussed above, the curve will take the form of

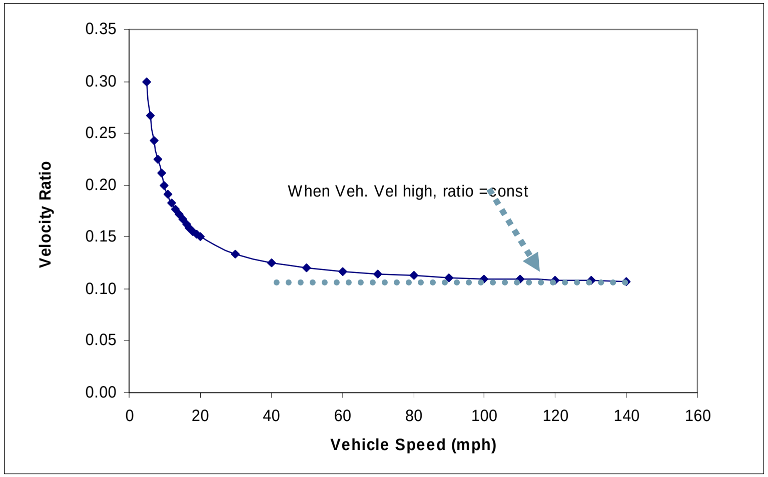


Chart-1 ε vs. vehicle speed U_V

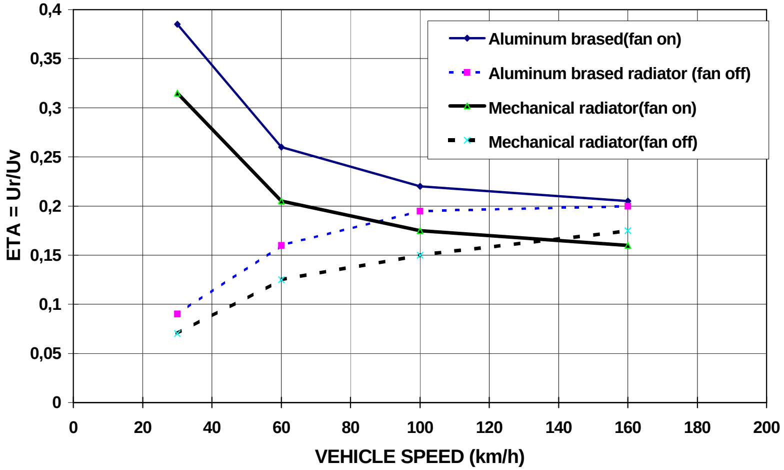


Chart-2 ε vs. vehicle speed U_V (Test Data)

Comparisons with vehicle data testing done by Valeo Engine Cooling [2], shows the trend of the curves are very similar.

Mathematical Expression- cont.

- **Impact of Fan & Heat Exchangers on Velocity Ratio, ε :**
  - **Variability of ε with fin density of heat exchanger airside pressure loss is shown in Chart 3**
  - **Variability of ε with fan system power level or airflow performance is shown in Chart 4**

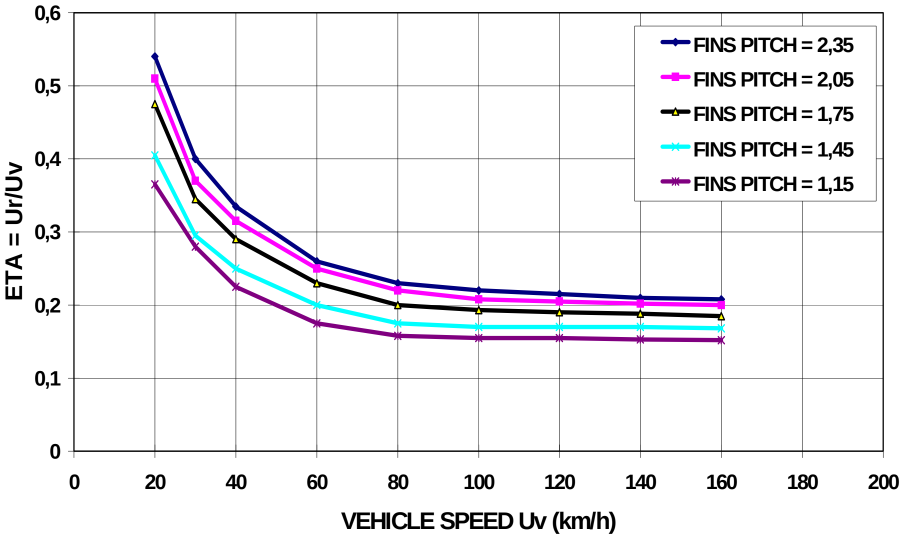


Chart-3 Impact of different heat exchanger on ε

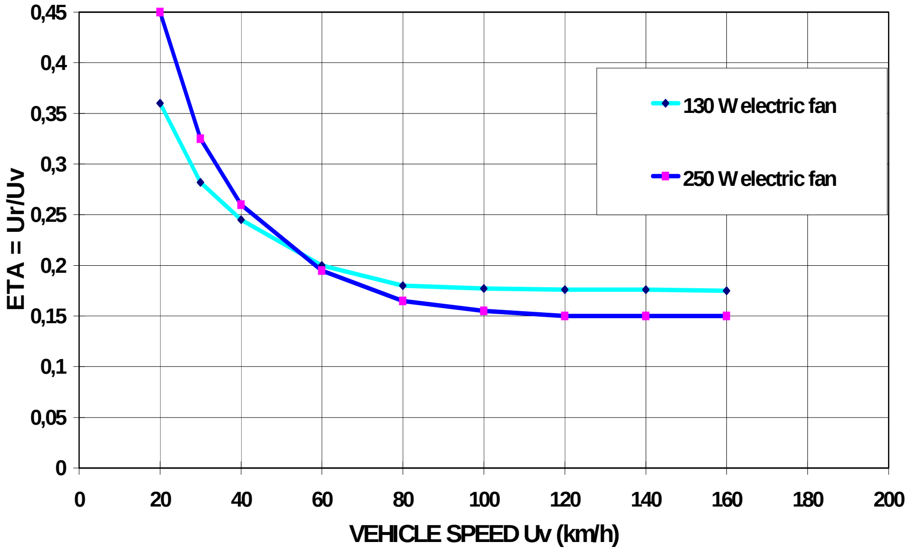


Chart-4 Impact of different Fan Systems on ε

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Vehicle Underhood Resistances Characters

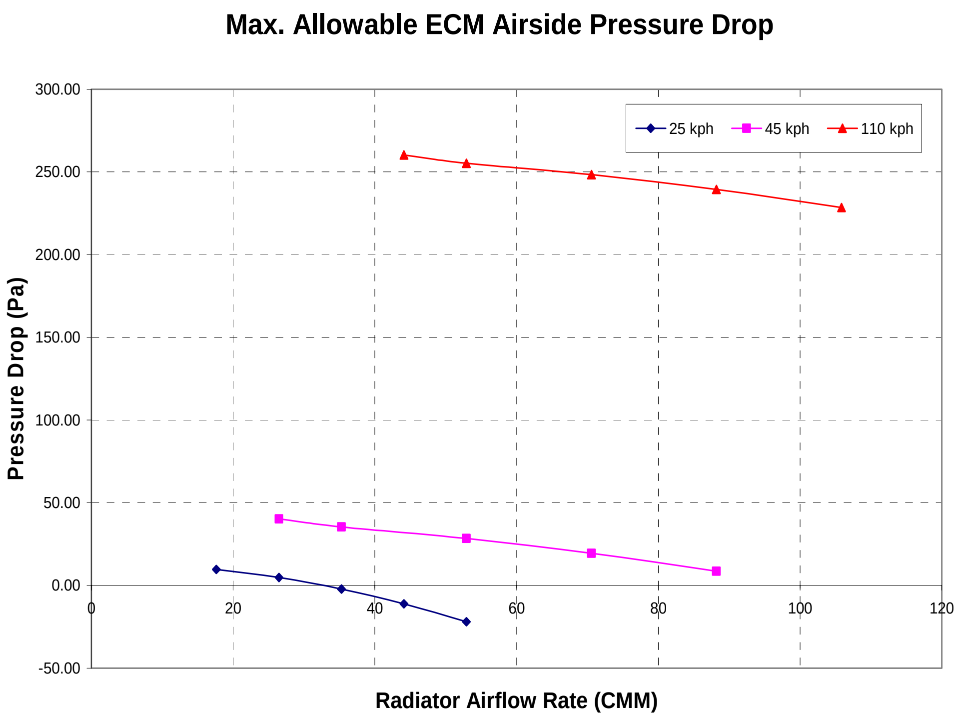
- **A general way to specify the vehicle underhood resistance characteristics**

$$\Delta P_{total} = \Delta P_{bay}(U_V, U_r) - \Delta P_{cp}(U_V) - \Delta P_{ex-contr}(U_V)$$

  - **Primary variance is with vehicle speed**
  - **Only the first term may depended on engine cooling module design details**
  - **Underhood resistance curves can be generated for different vehicle speeds for different combinations of fan power level or heat exchanger stack airside pressure loss levels**

Vehicle Underhood Resistances Characters

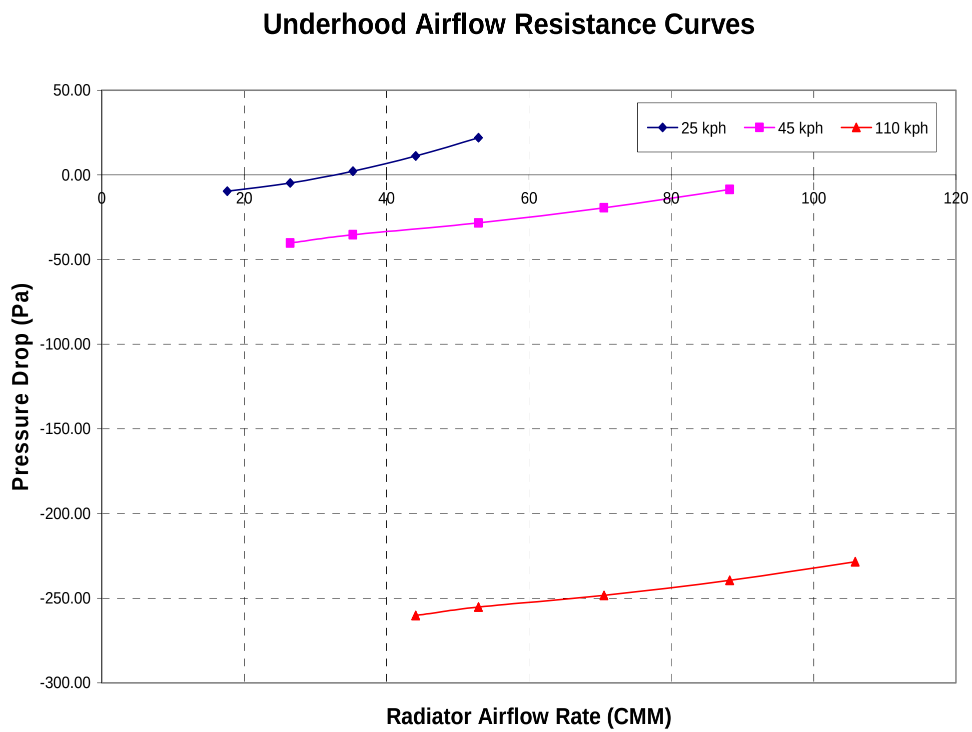
- **Examples to specify the vehicle underhood resistance characteristics**
  1. **Max. allowable engine cooling module air side pressure drops.**
     - **Defined as:** $\Delta P_{\max} = (\Delta P_{hex} - \Delta P_{fan}) = -(\Delta P_{bay} - \Delta P_{cp} - \Delta P_{ex-contr})$



$$\Delta P_{\max} \approx -constU_V^2 - \Delta P_{bay}(U_V, U_r)$$

Vehicle Underhood Resistances Characters

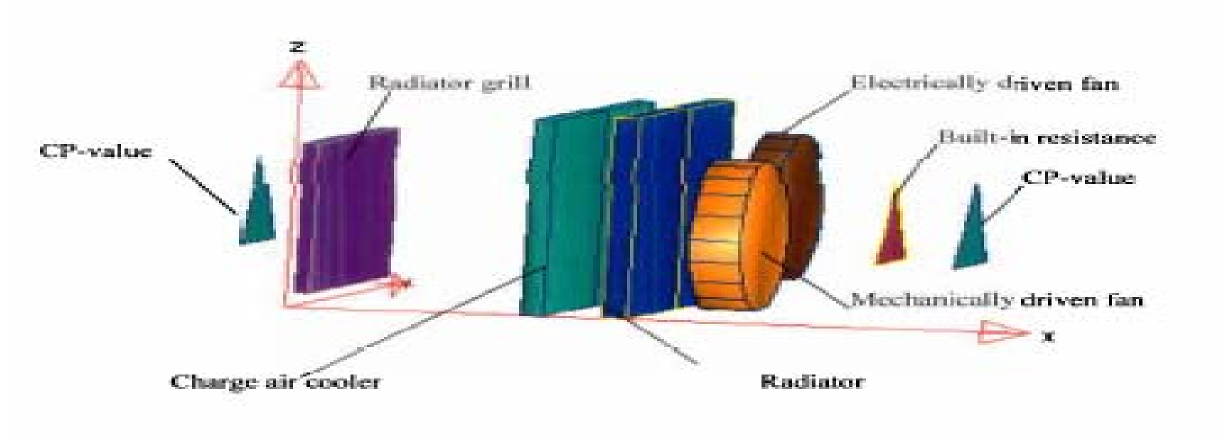
- **Examples to specify the vehicle underhood resistance characteristics**
  2. **Total underhood air side pressure drops.**
     – **Defined as:** $\Delta P_{total} = (\Delta P_{bay} - \Delta P_{cp} - \Delta P_{ex-contr})$



$$\Delta P_{total} \approx const U_V^2 + \Delta P_{bay}(U_V, U_r)$$

KULI 1-D Underhood Airflow Simulation

- **KULI model simulation assumptions**
  - ➔ 1-D modeling, but allows for various flow paths
  - ➔ Can be applied for isothermal flow
  - ➔ Incompressible flow
  - ➔ With heat exchangers or equivalence area resistance models
  - ➔ Steady state simulation mainly
  - ➔ Need Cps and other parameter to simulate the entire underhood
- **Typical KULI modeling format**



KULI 1-D Underhood Airflow Simulation

- **Two ways to define the inlet Cp [3]**
  1. **Based on relative vehicle speed, which is measured as the front grille is fully covered.**

$$Cp = \frac{\Delta P}{\frac{1}{2}\rho(U_V - U_{inlet})^2}$$

  2. **Based on absolute vehicle speed, which is in line with detailed CFD simulation, is same as the commonly used definition**

$$Cp = \frac{\Delta P}{\frac{1}{2}\rho U_V^2}$$

- **In the practical application, especially for new vehicle development, without existing front grilles, it is difficult to use either method to define the inlet Cp or to de-couple inlet Cp from CFD simulation data.**

KULI 1-D Underhood Airflow Simulation

Example of application

KULI relative Cp definition can be calibrated to closely match CFD based results of vehicle airflow behavior, loosely based on the velocity of radiator-Ur, for various vehicle speeds using isothermal analysis on Excel.

Kuli Results vs. Excel Data

Air volumetric flow for Radiator			
CFM	1643.1	1903.5	2083.2
CMS	0.775	0.898	0.983
Kuli-CMM	46.5	53.9	59.0
Fan Data-CMM	47.0	54.0	58.5
Error	1.0%	0.2%	-0.8%
Veh.Speed -KPH	50	80	110

Values in KULI Model

Cp values		**Built in Reistance**	
Cp inlet	0.4	Resistance -1	80
Cp outlet	-0.2	Resistance -2	25

Test Condition:

Density	1.136	kg/m^3
Temperature	38	^{o} C

Discussion & Conclusion

- Discussions
  - → Current way to define underhood vehicle resistance is valid
  - → How can KULI be easily used for new vehicle development using outputs from CFD based analysis?
  - → Can Cps and other parameter be provided to the thermal system suppliers as separate data extracted from vehicle level CFD simulation?
  - → How can partial shroud and other unusual flow pathways be integrated into KULI application?

Discussion & Conclusion

- Conclusions
  - ➔ CFD Data must be provided to assist 1-D modeling for new vehicle development
  - ➔ 1-D model can provide general ideas and trends for underhood airflow analysis.
  - ➔ KULI 1-D can provide accurate simulation results when correlation is done to match KULI Cp definitions and results from CFD predictions

Reference

- References

1. W.M. Kays, A.L. London, *Compact Heat Exchangers*, McGRAW-HILL,1964
2. Ngy Srun AP, A Simple Engine Cooling System Simulation Model, SAE Paper, 1999-01-0237,1999
3. KULI Online Help, *KULI Theory*, Magna Steyr,2006