

# ***KULI Air Side***

*Christoph Stroh*



**drivetrain components  
and systems**



**engines and  
engine components**



**axle and  
chassis modules**



***Engineering Center Steyr  
GmbH & Co KG***

***driven by passion***

- Theoretical considerations
- cp-values
- Fans
- Uneven air flow - CFD interface

## *The theoretical foundation*

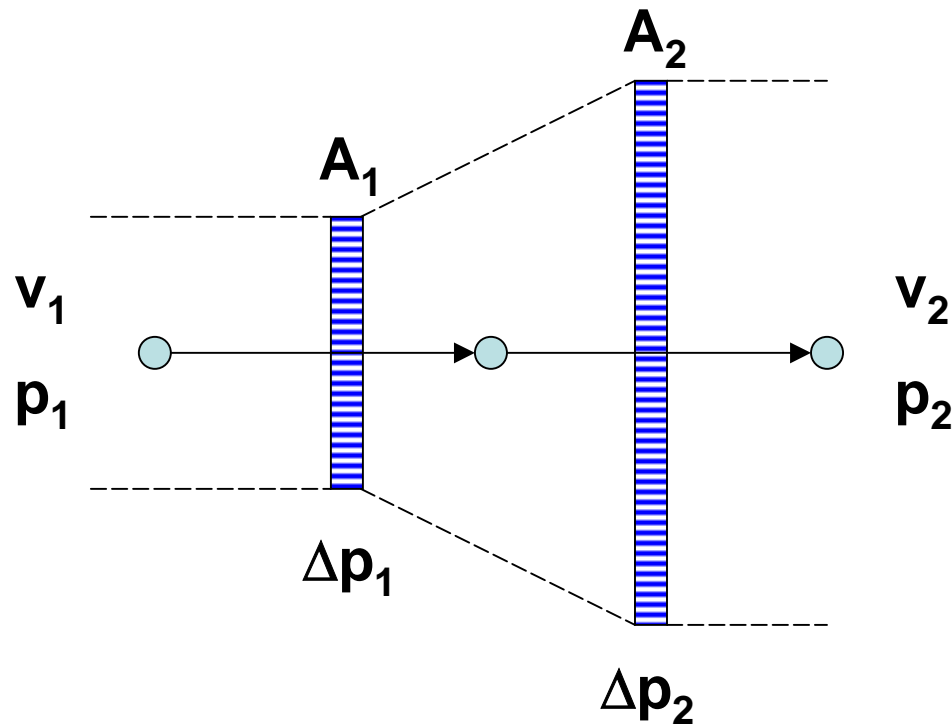
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$$\underbrace{p_{\text{stat}} + \underbrace{\frac{\rho}{2} v^2}_{= p_{\text{dyn}}}}_{= p_{\text{tot}}} (+ \rho g h) = \text{constant}$$

↑  
**Bernoulli**

- $p_{\text{stat}}$  = static pressure
- $p_{\text{dyn}}$  = dynamic pressure
- $p_{\text{tot}}$  = total pressure
- $\rho$  = density
- $v$  = velocity
- $h$  = height
- $g$  = gravity

# *A simple air path*



## Assumptions:

- $\rho = \text{constant} = 1$
- $p_{1,\text{stat}} = 1 \text{ bar}$
- $v_1 = 20 \text{ m/s}$
- $A_1 = 0,5 \text{ m}^2$
- $A_2 = 1 \text{ m}^2$
- $\Delta p_1 = \Delta p_2 = 200 \text{ Pa}$
- $p_{2,\text{stat}} = ??$

# Method 1: Bernoulli holds *between* components

$$A_2 = 2A_1 \Rightarrow v_2 = v_1 / 2 = 10 \text{ m/s}$$

$$p_{1,\text{dyn}} = \frac{\rho}{2} v_1^2 = \frac{1}{2} 400 = 200 \text{ Pa}$$

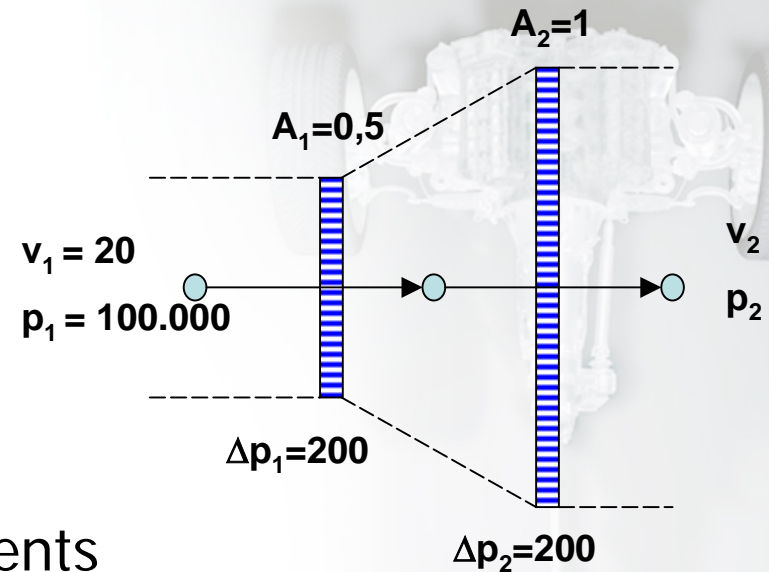
$$p_{2,\text{dyn}} = \frac{\rho}{2} v_2^2 = \frac{1}{2} 100 = 50 \text{ Pa}$$

Bernoulli holds *between* the components

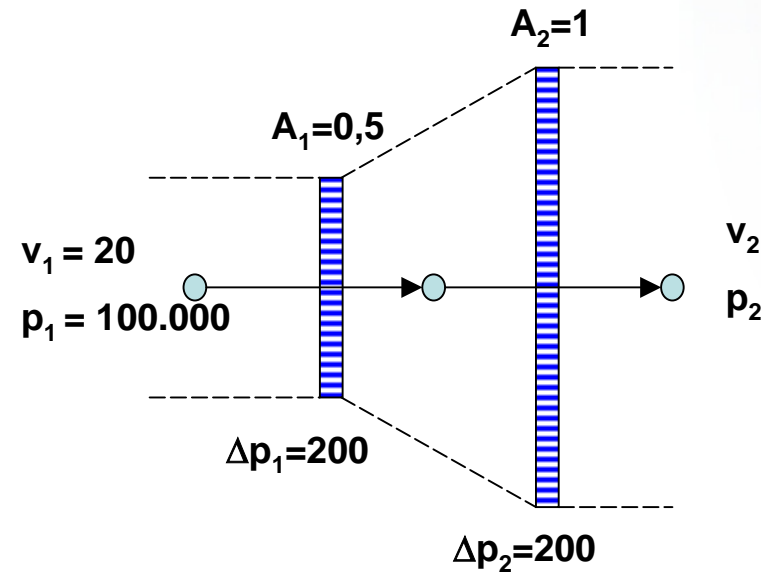
=>  $p_{\text{tot}}$  = konstant

=>  $p_{\text{stat}}$  increases by  $200 - 50 = 150 \text{ Pa}$ !

$$p_{2,\text{stat}} = p_{1,\text{stat}} - \Delta p_1 + 150 - \Delta p_2 = 99.750 \text{ Pa}$$



## Method 2: Static pressure constant between components



$$p_{2,\text{stat}} = p_{1,\text{stat}} - \Delta p_1 - \Delta p_2 = 99.600 \text{ Pa}$$

## *How does KULI calculate the air path?*

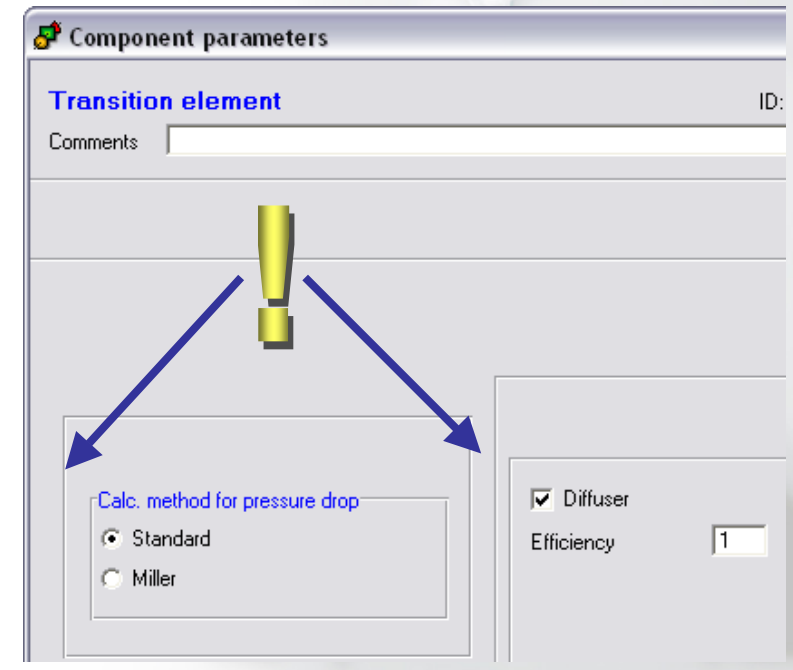
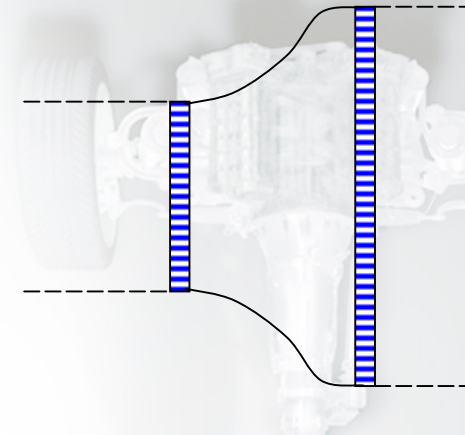
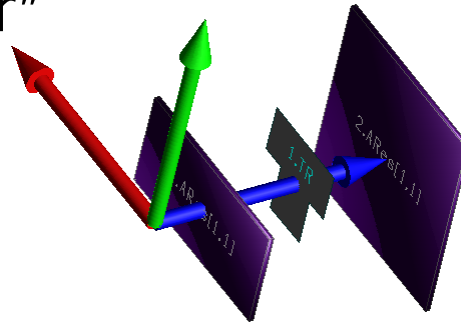
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- KULI uses Method 2, i.e.,  $p_{\text{stat}}$  is constant, because
  - in reality in most cases  $p_{\text{dyn}}$  cannot be regained when the area increases.
  - essentially only the area change from the first to the last component in the air path is relevant, all other changes cancel out.
  - a change of pressure due to a change of area can easily be packed into a built-in resistance.
- Investigations showed that there can even be a static pressure drop from small inlet grille areas to the larger radiator area, mainly due to swirls and turbulences.

## Constant total pressure in KULI

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- In special conditions it makes sense to use constant total pressure, e.g. for diffuser-like configurations without turbulences.
- In KULI use a transition element and choose "Diffuser"
- The "Efficiency" defines the part of the dynamical pressure difference that will be converted into static pressure.





- Theoretical considerations
- cp-values
- Fans
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## Air flow at air inlet: $c_p$ -values

$p_\infty$ ,  $p_i$ : static pressure ambient and entry, resp.

$v_\infty$ ,  $v_i$ : driving speed and air entry velocity

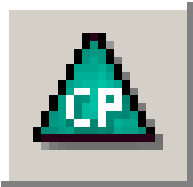


$p_i$   $v_i$

$p_\infty$   
 $\rho_\infty$   
 $v_\infty$

## *New options for cp value*

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### Determination of pressure difference

- ☒ Relative Method  
Measurement: closed; Analysis: open
- ☐ Absolute Method  
Measurement: open or Values from CFD; Analysis: open
- ☐ Total Pressure Method  
Measurement: closed; Analysis: open

$$\text{rel.: } \Delta p = cp \times \frac{\rho}{2} \times (v_{\infty} - v_{inlet})^2$$

$$\text{abs.: } \Delta p = cp \times \frac{\rho}{2} \times (v_{\infty})^2$$

$$\text{tot.: } \Delta p = \frac{\rho}{2} \times (cp \times v_{\infty}^2 - v_{inlet}^2)$$

## *cp-values - the 3 methods*

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### **“Absolute method”**

$$c_p = \frac{\Delta p}{\frac{\rho}{2} v_\infty^2} \Leftrightarrow \Delta p = c_p \frac{\rho}{2} v_\infty^2$$

### **“Relative method”**

$$c_p = \frac{\Delta p}{\frac{\rho}{2} (v_\infty - v_i)^2} \Leftrightarrow \Delta p = c_p \frac{\rho}{2} (v_\infty - v_i)^2$$

### **“Total pressure method”**

$$c_p = \frac{\Delta p + \frac{\rho}{2} v_i^2}{\frac{\rho}{2} v_\infty^2} \Leftrightarrow \Delta p = \frac{\rho}{2} (c_p v_\infty^2 - v_i^2)$$

$$(\Delta p = p_i - p_\infty)$$

## *cp-value: Absolute method*

$$c_p = \frac{\Delta p}{\frac{\rho}{2} v_\infty^2} \Leftrightarrow \Delta p = c_p \frac{\rho}{2} v_\infty^2 \Leftrightarrow p_i = p_\infty + c_p \frac{\rho}{2} v_\infty^2$$

- cp-value defines which part of the dynamical pressure can be converted into static pressure.
- The determination of the cp-value must be carried out for open condition (i.e. with engine compartment air flow)
- The cp-value and thus the pressure increase only depend on the driving speed; the area of the cp-value has no influence!
- The area of the cp-value is used in the postprocessor to compute the flow velocity in the cp-value component; this however is only an output value and does not influence the computation.

## *cp-value: Relative method*

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$$c_p = \frac{\Delta p}{\frac{\rho}{2} (v_\infty - v_i)^2} \Leftrightarrow \Delta p = c_p \frac{\rho}{2} (v_\infty - v_i)^2$$

- Purpose of this method: Determination of the cp-value for closed condition, simulation then for open condition => different formulas for determination and usage (simulation)

### **Determination (closed)**

$$c_p = \frac{\Delta p}{\frac{\rho}{2} v_\infty^2}$$

### **Usage (open)**

$$\Delta p = c_p \frac{\rho}{2} (v_\infty - v_i)^2$$

- The pressure increase depends on  $v_i$  and thus on the area of the cp-value (since  $v_i = \text{volume flow} / \text{area}$ )! This dependency can be significant!



## *cp-value: Total pressure method (suggested by VW)*

$$c_p = \frac{\Delta p + \frac{\rho}{2} v_i^2}{\frac{\rho}{2} v_\infty^2} = \frac{p_{i,\text{tot}} - p_\infty}{\frac{\rho}{2} v_\infty^2} \Leftrightarrow \Delta p = \frac{\rho}{2} (c_p v_\infty^2 - v_i^2)$$

- Idea of this method: Total pressure at entry should be constant, no matter if the entry is open or closed => this method should be useable for open and closed models!

**cp-value describes total pressure drop from ambient to air inlet.**

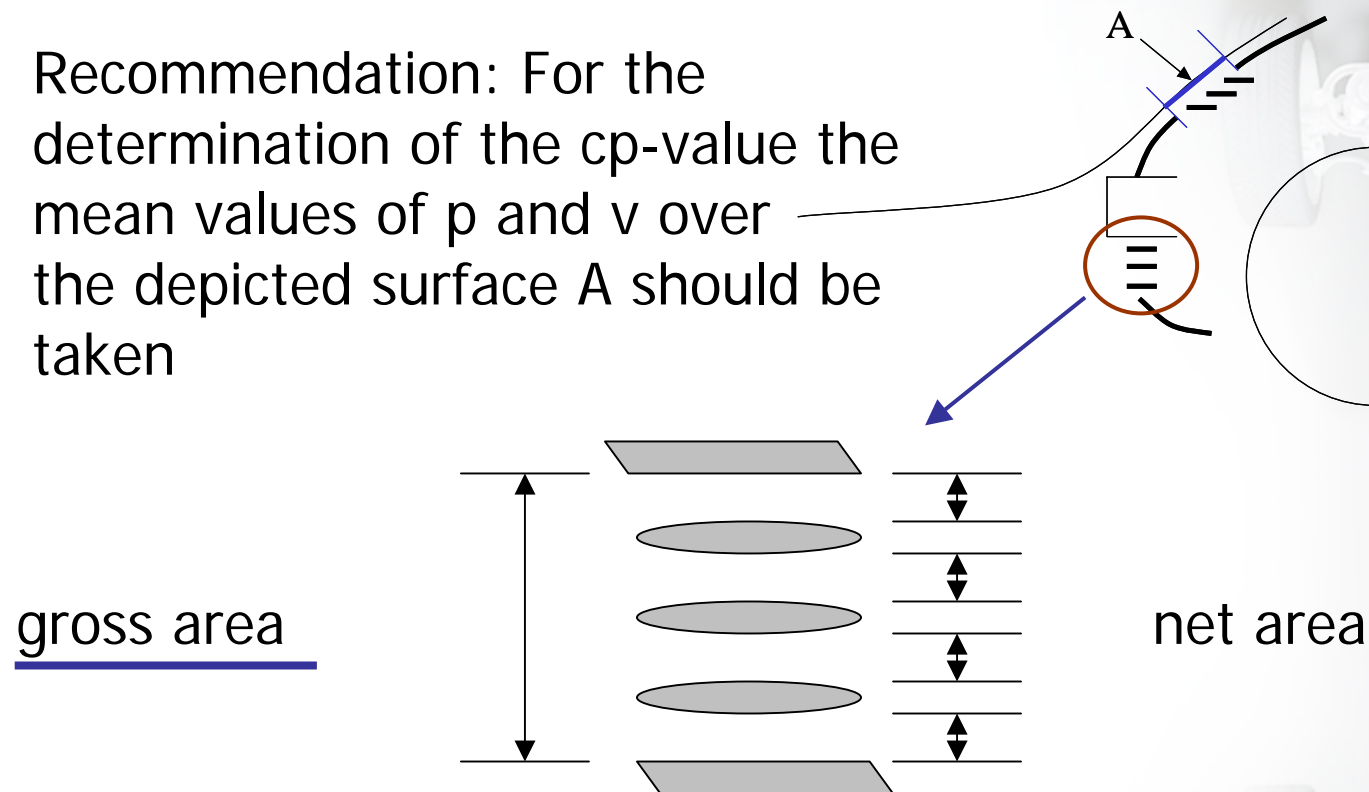
$$p_{\infty,\text{tot}} = p_\infty + \frac{\rho}{2} v_\infty^2 > p_\infty + c_p \frac{\rho}{2} v_\infty^2 = p_i + \frac{\rho}{2} v_i^2 = p_{i,\text{tot}}$$

- The pressure increase depends on  $v_i$  and thus on the area of the cp-value (since  $v_i = \text{volume flow} / \text{area}$ )! This dependency can be significant!

# Areas of $cp$ -values

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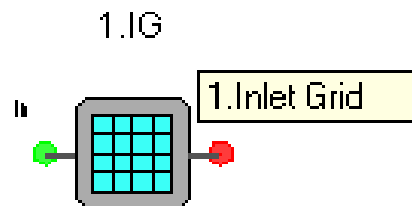
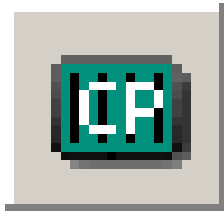
Recommendation: For the determination of the  $cp$ -value the mean values of  $p$  and  $v$  over the depicted surface  $A$  should be taken



In the  $cp$ -value component the gross area should be used, since pressure drops which are due to the shape of the grille are modeled in the area resistance describing the grille.



# Inlet grid



Definition of  
cp value and  
pressure loss  
of grill in one  
component

General data | CP value | Pressure loss

User: TZS  
Date (0=current): Mittwoch, 27. Oktober 2004 15:02:32  
Title: Example  
Memo:

General data | CP value | Pressure loss

Width [mm]: 500  
Height [mm]: 300  
Depth [mm]: 10

Type: CAR  
No.: NO001  
Manufacturer: KK  
Series: CL001  
Measrd. data file: MF007

CP value: 0.8

Determination of pressure difference

☒ Relative Method  
Measurement: closed; Analysis: open

☐ Absolute Method  
Measurement: open or Values from CFD; Analysis: open

☐ Total Pressure Method  
Measurement: closed; Analysis: open

rel.:  $\Delta p = cp \times \frac{\rho}{2} \times (v_{\infty} - v_{inlet})^2$   
abs.:  $\Delta p = cp \times \frac{\rho}{2} \times (v_{\infty})^2$   
tot.:  $\Delta p = \frac{\rho}{2} \times (cp \times v_{\infty}^2 - v_{inlet}^2)$

☒ Defined by characteristic curve(s)  
☐ Defined by parameters

[1]

Flow rate	Pressure drop
0.1	3
0.2	6.2
0.3	12
0.4	18
0.5	25
0.6	32
0.7	42
0.8	49
0.9	59
1	71
1.1	83
1.2	94
1.5	134
2	218

- Theoretical considerations
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# *How to determine characteristic curves of fans?*

- How and where are pressures to be measured?
  - is regulated in DIN-Norm 24163
- Should I use static or total pressure differences?
  - depends on test bench; rather take static pressure differences
  - in KULI this is not a problem, since the difference between the two version can be corrected with a built-in resistance
- Should I use a deflector plate ("Prallplatte")?
  - Measurements with deflector plate yield more realistic characteristic curves
  - The difference with/without deflector plate cannot be compensated with a standard built-in resistance
  - Problem of normalization
    - how big should be the deflector plate?
    - what would be the distance between fan and deflector plate?

# Fan measurement - Standard test bench (DIN 24163)

## Determination of pressure increase Part 2, Section 8.1.3

### Blowing unblocked $\Delta p_{fa}$

#### 1) Measurement of total pressure $p_{t1}$

$$\Delta p_{fa} = p_a - p_{t1} = 100000 - 99900 = 100 \text{ Pa}$$

#### 2) Measurement of static pressure $p_{st1}$

$$\bar{c}_5 = \dot{V}_1 / A_5$$

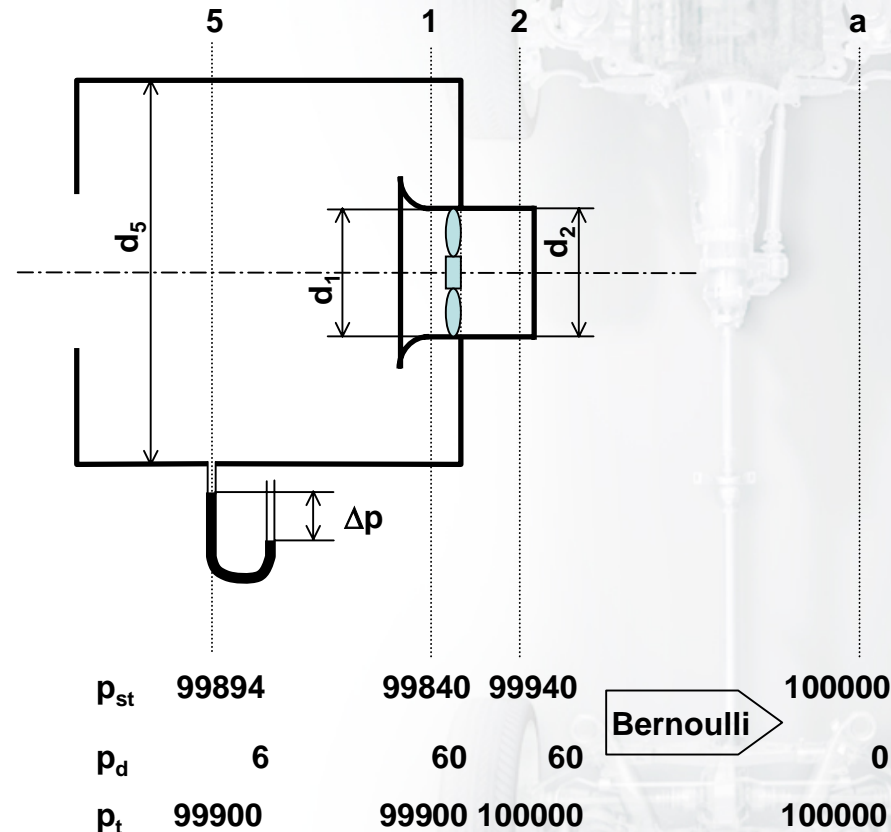
$$\Delta p_{fa} = p_a - (p_{st5} + \frac{\rho_1}{2} \cdot \bar{c}_5^2) = \Delta p - \frac{\rho_1}{2} \cdot \bar{c}_5^2$$

$$= 100000 - 99894 - 6 = 100 \text{ Pa}$$

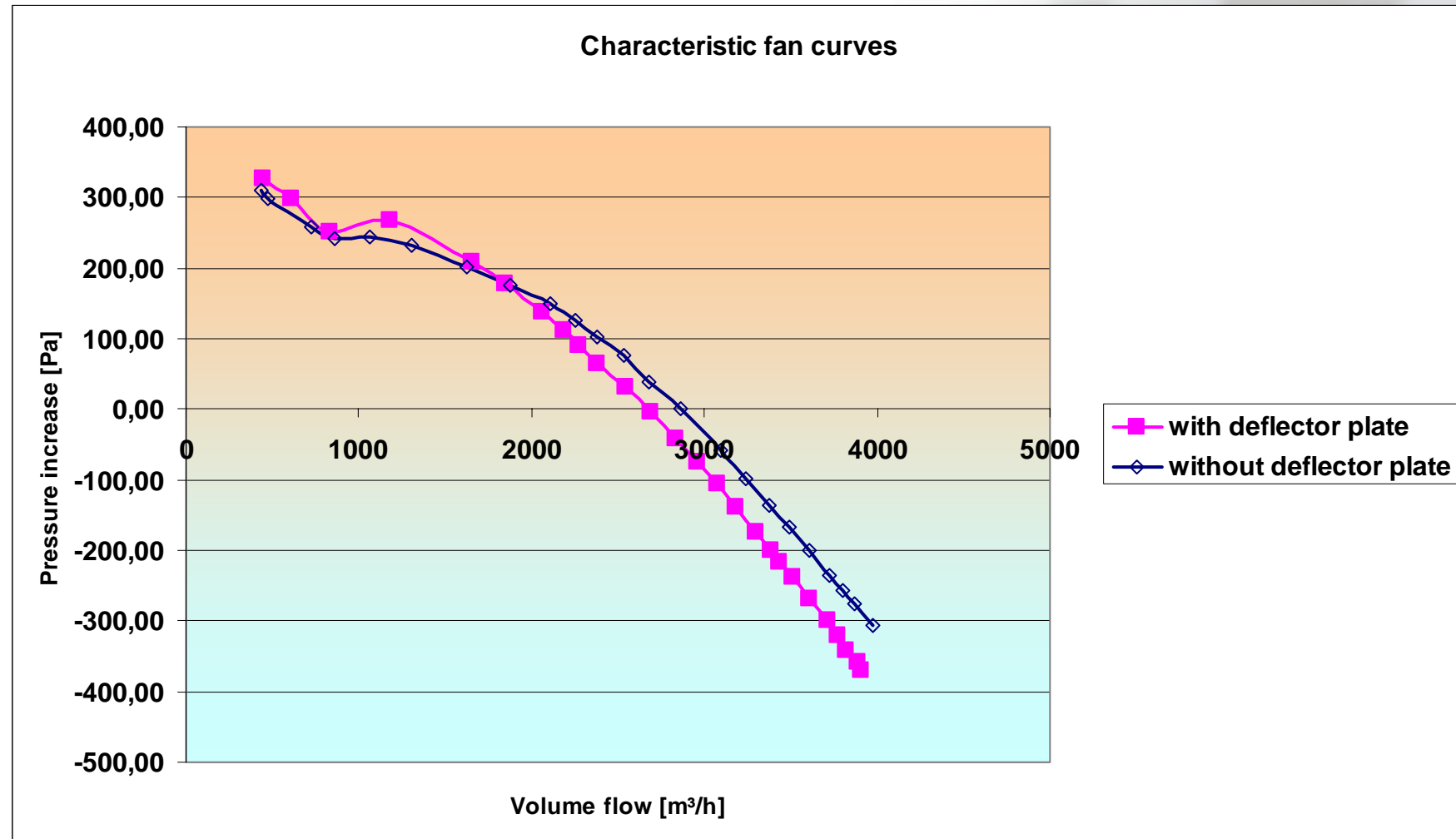
### Total pressure increase $\Delta p_t$

$$\bar{c}_2 = \dot{V}_2 / A_2$$

$$\Delta p_t = \Delta p_{fa} + \frac{\rho_2}{2} \cdot \bar{c}_2^2 = 100 + 60 = 160 \text{ Pa}$$



# Characteristic fan curves with and without deflection plate



# Regression of fan curves



General data Charac. curves

Ambient medium: Air  
Entry temp. of cooling air [°C]: 20  
Entry press. of cooling air [hPa]: 1013  
Air humidity [%]: 50

Unit of flow rate: kg/s  
Unit of press.loss: N/m²  
Unit of power: kW

☒ Calculate with regressed data  
☒ Use optional speed input  
☒ Regression

Nominal speed [rpm]: 2500

Pressure number regression

Order: 4  
Relative filter range: 0.01  
Absolute filter range: 0.01

Efficiency regression

Order: 6  
Absolute filter range: 0.01  
Relative filter range: 0.01

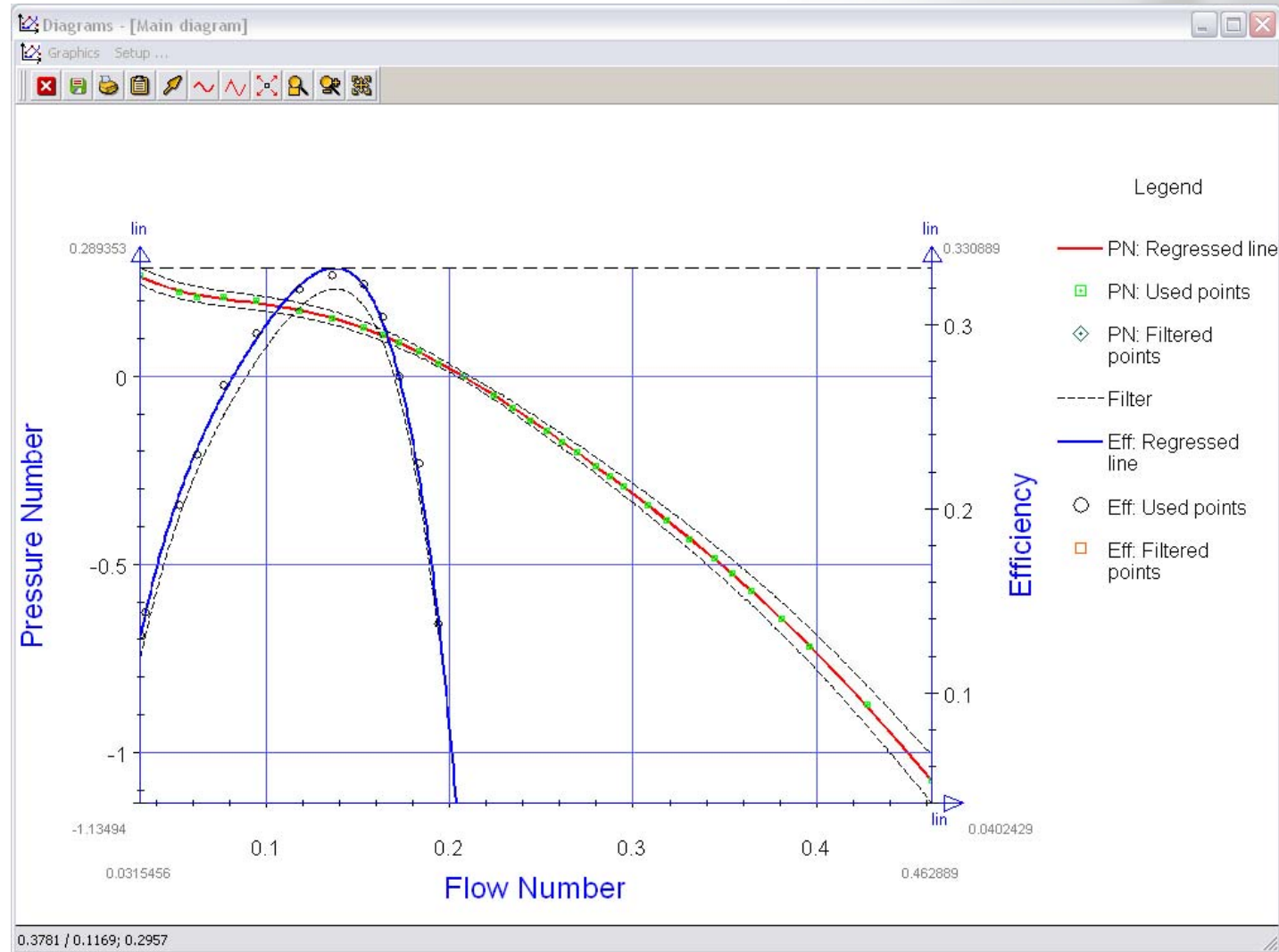
Cycling: 6

[1] [Reg]

RPM: 2500

Flow rate	Pressure drop	Power	RPM (option)
0.496	484.59	0.5486	2500
0.515	482.87	0.5546	2500
0.535	481.09	0.5569	2500
0.555	479.21	0.5566	2500
0.575	477.19	0.5546	2500
0.594	474.96	0.5514	2500
0.614	472.51	0.5478	2500
0.634	469.79	0.544	2500
0.654	466.77	0.5405	2500
0.674	463.41	0.5373	2500
0.693	459.69	0.5347	2500
0.713	455.59	0.5327	2500
0.733	451.08	0.5313	2500
0.753	446.13	0.5305	2500
0.773	440.73	0.5304	2500

# Regression of fan curves (2)





## *Fan regression - how to use it*

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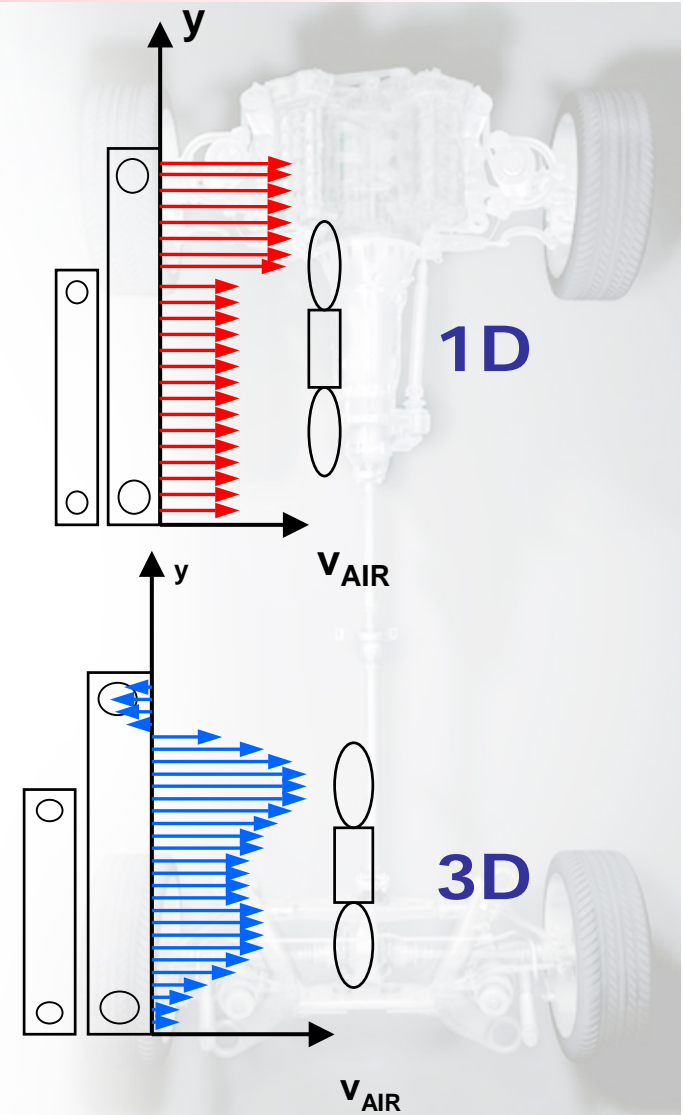
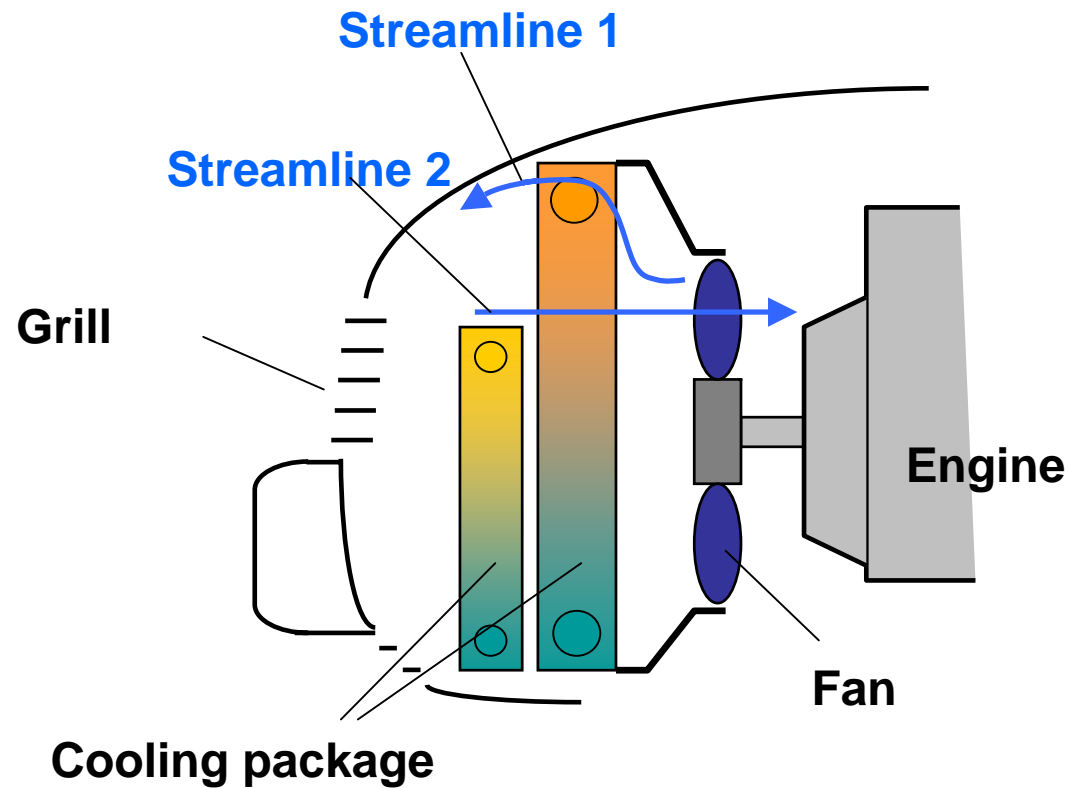
- Regression can be used to smooth out measurement errors
- Regression can be used to combine measurement data of resistance curve (fan off) and pressure increase curve (fan on)
- Regression can be used to convert measurement data of electric fan into mechanical fan, allowing modelling of continuous electric fan
- Usually raw data is simply copied from Excel into KULI
- Description of usage in online help:
  - KULI base -> Components -> Fans -> Fan regression



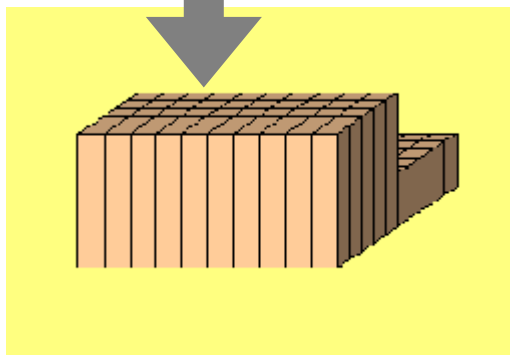
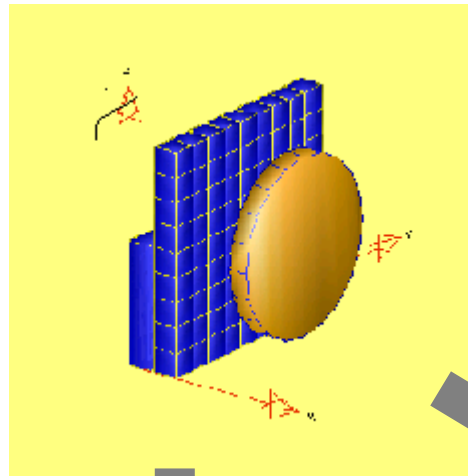
- Theoretical considerations
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# 1D-3D Principles

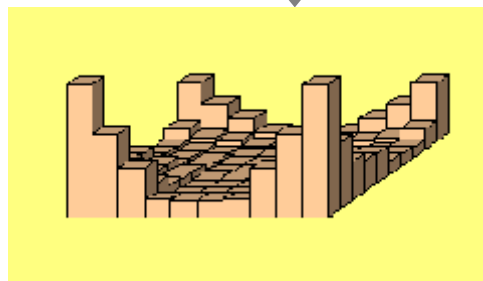


Cooling System



$\zeta$ -values of  
block elements

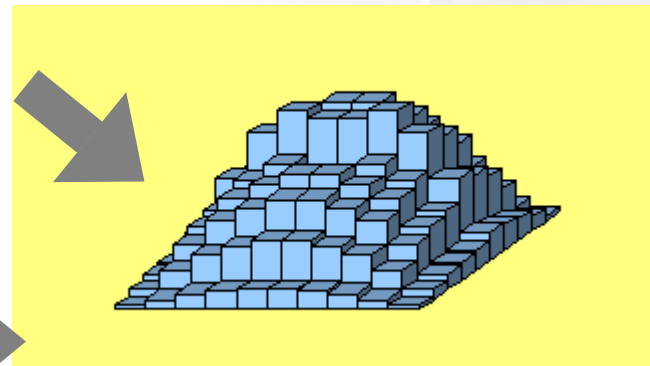
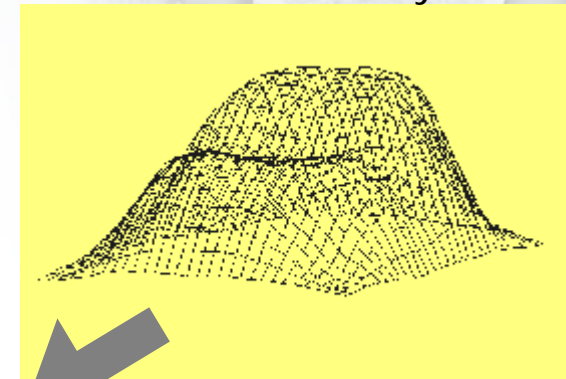
Air flow  
in block



matrix of  
correction factors for  
 $\zeta$ -values in block

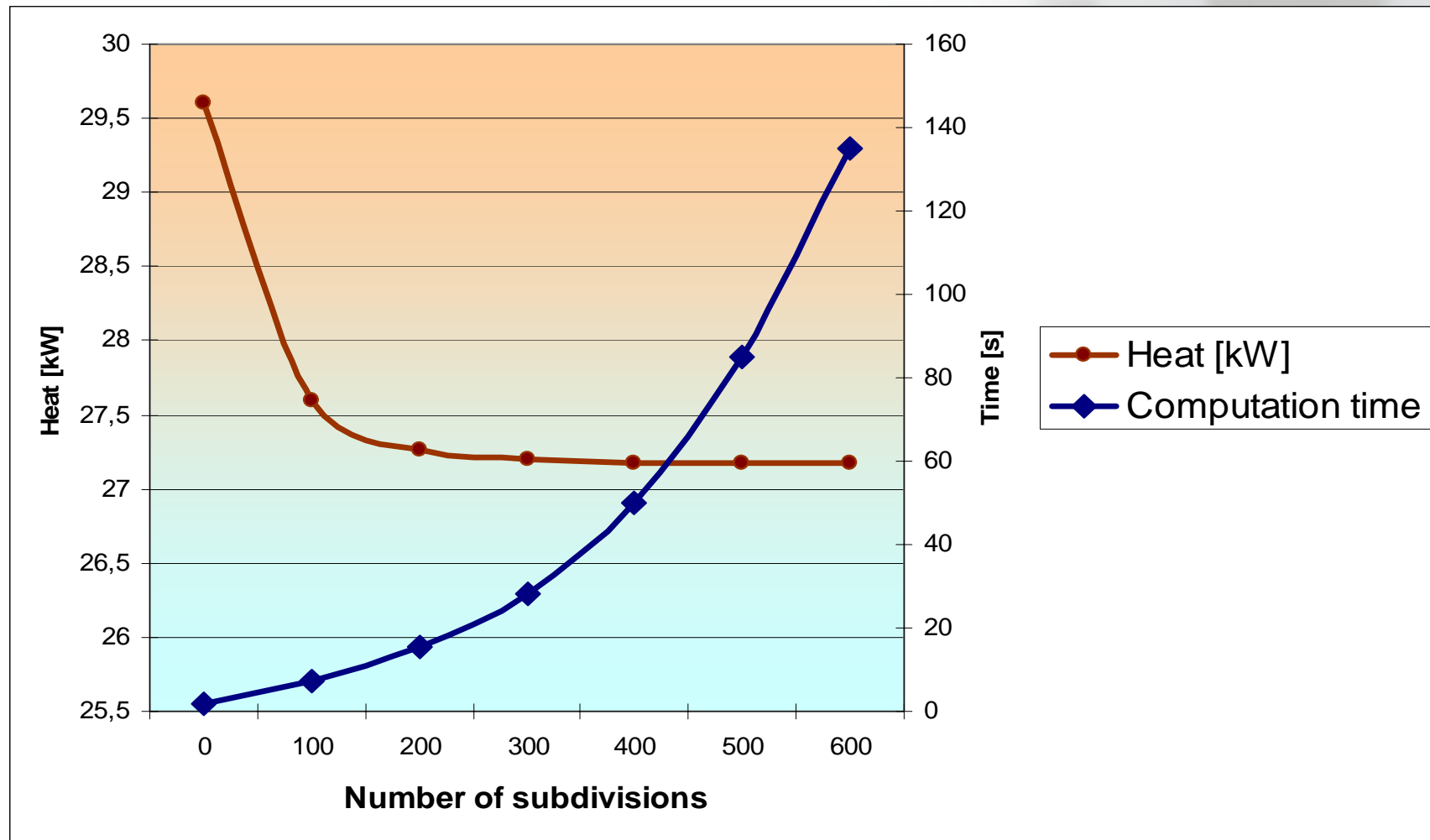


Air velocity distribution  
from CFD analysis



Air velocity distribution  
on cooling system block

# Accuracy and Time vs. Number of Subdivisions



# *Motivation for variable resistance matrix*

- Velocity distribution on surface of component is not equal for different conditions
- Velocity distributions may depend on
  - driving speed
  - fan rpm
  - air flaps
  - ...
- Standard implementation of resistance matrix in KULI requires separate KULI models for different configurations
- Standard implementation of resistance matrix is thus not suitable for transient simulation
- Resistance matrix needs to be more flexible during simulation

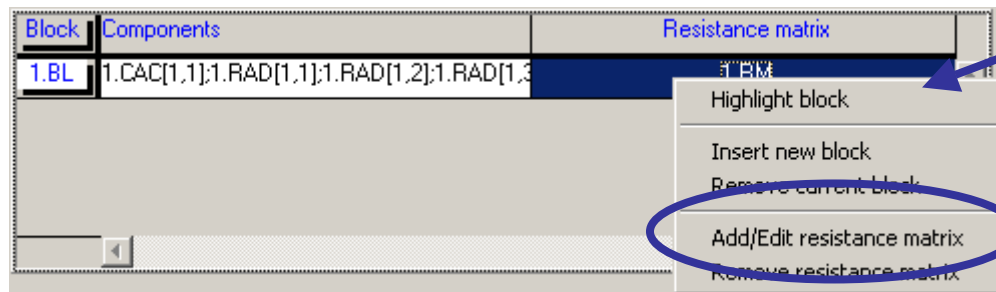
## *New resistance matrix method in KULI*

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- Generation of resistance matrix as before
- Several resistance matrices can now be assigned to a single block
- Each resistance matrix is assigned to a certain driving speed and/or one other parameter
- This second parameter is defined via COM-objects. Hence, any sensor can act as this second parameter
- During computation the zeta-correction factors are obtained via interpolation depending on the current driving speed and/or value of the second parameter

## Usage (1)

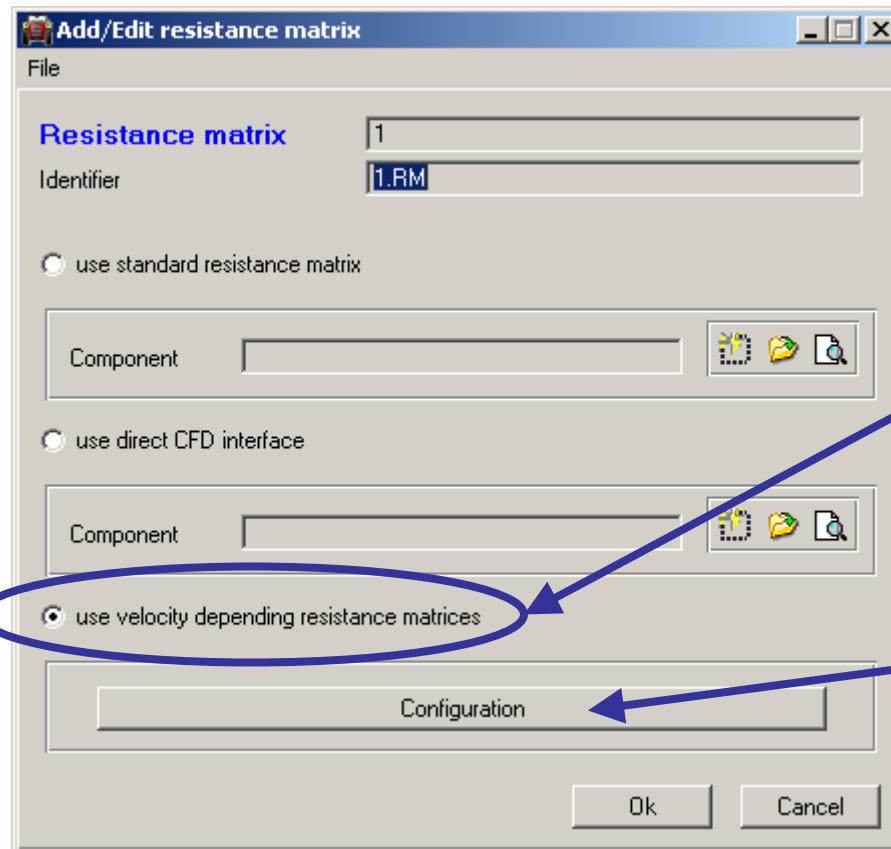
A variable resistance matrix is added to a block in the same way as a standard resistance matrix



context menu

add resistance matrix

## Usage (2)



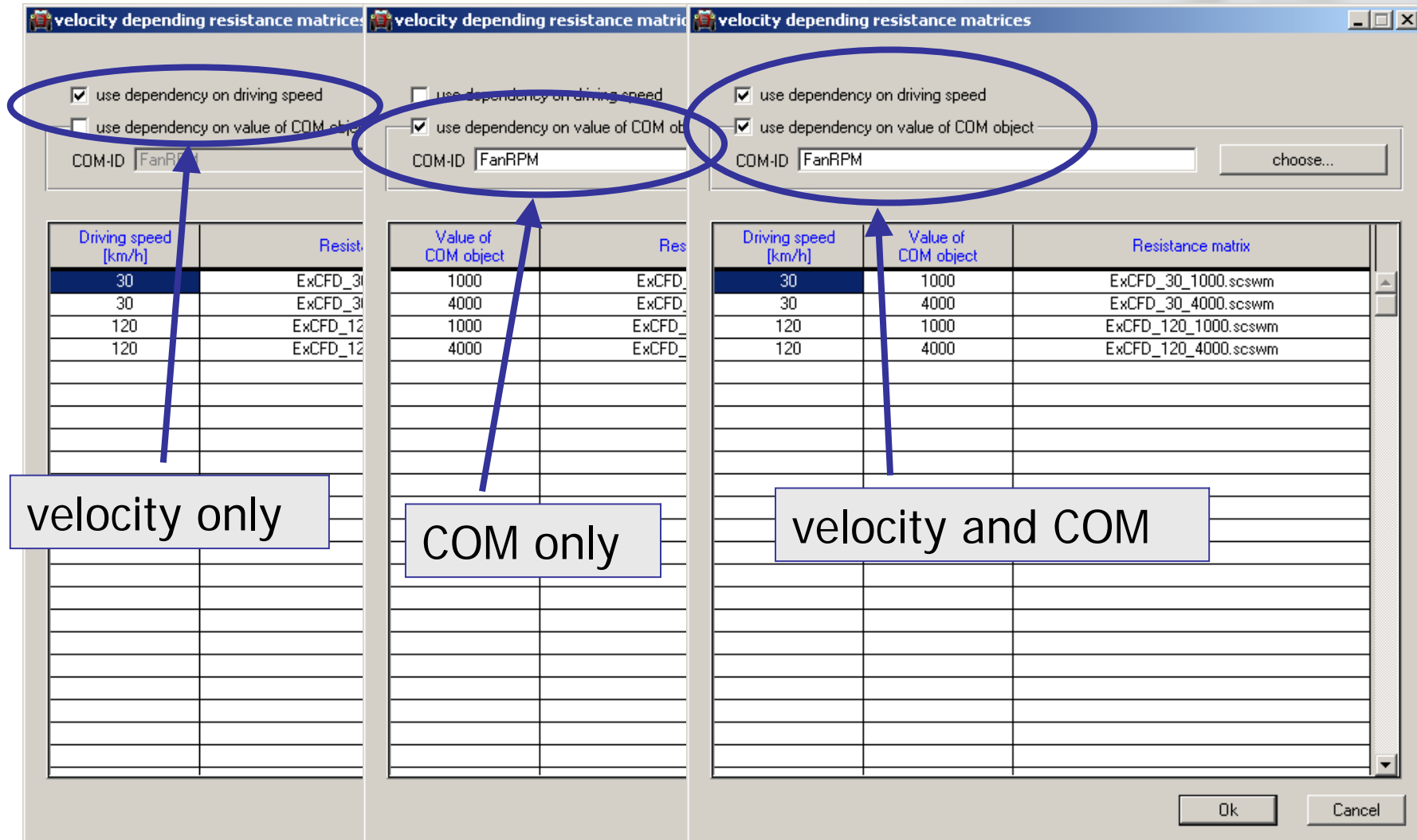
choose type of  
resistance matrix

click on  
„Configuration“



## Usage (3) - Dependence on...

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The image shows three instances of the 'velocity depending resistance matrices' dialog box, each illustrating a different dependency configuration. Blue circles and arrows highlight the specific settings and the corresponding data tables.

**velocity only:** The 'use dependency on driving speed' checkbox is checked, and 'use dependency on value of COM object' is unchecked. The COM-ID is 'FanRPM'. The table shows resistance values for driving speeds of 30 and 120 km/h.

Driving speed [km/h]	Resistance
30	ExCFD_30
30	ExCFD_30
120	ExCFD_120
120	ExCFD_120

**COM only:** The 'use dependency on driving speed' checkbox is unchecked, and 'use dependency on value of COM object' is checked. The COM-ID is 'FanRPM'. The table shows resistance values for COM object values of 1000 and 4000.

Value of COM object	Resistance
1000	ExCFD_1000
4000	ExCFD_4000
1000	ExCFD_1000
4000	ExCFD_4000

**velocity and COM:** Both 'use dependency on driving speed' and 'use dependency on value of COM object' checkboxes are checked. The COM-ID is 'FanRPM'. The table shows resistance values for combinations of driving speed (30, 120 km/h) and COM object value (1000, 4000).

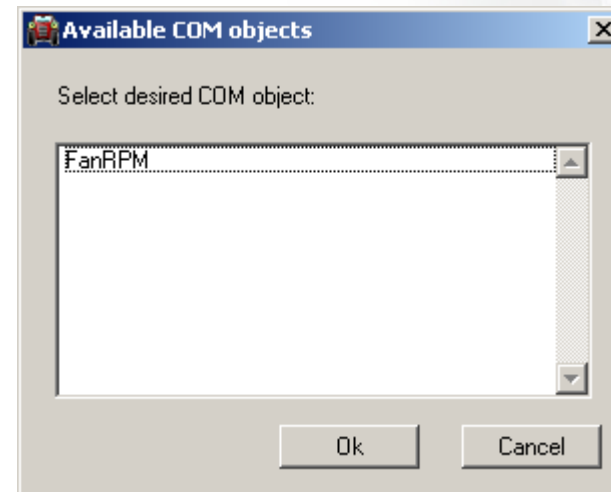
Driving speed [km/h]	Value of COM object	Resistance matrix
30	1000	ExCFD_30_1000.scswm
30	4000	ExCFD_30_4000.scswm
120	1000	ExCFD_120_1000.scswm
120	4000	ExCFD_120_4000.scswm

## *Usage (4) - Choice of COM object*

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☒ use dependency on value of COM object  
COM-ID

list of all available COM objects in model is displayed;  
COM ID can also be entered manually



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[illegible]

## *Some implementation details*

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- Interpolation is done (bi)linear. Hence, only two values for each variable (velocity and/or COM value) are necessary
- No extrapolation is done; boundary values are taken if current operating point is outside defined range
- If dependency on two variables is selected, then for each velocity value all COM values must appear in the configuration table (and vice versa)

*Thank you for your attention!*



**drivetrain components  
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**engines and  
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