

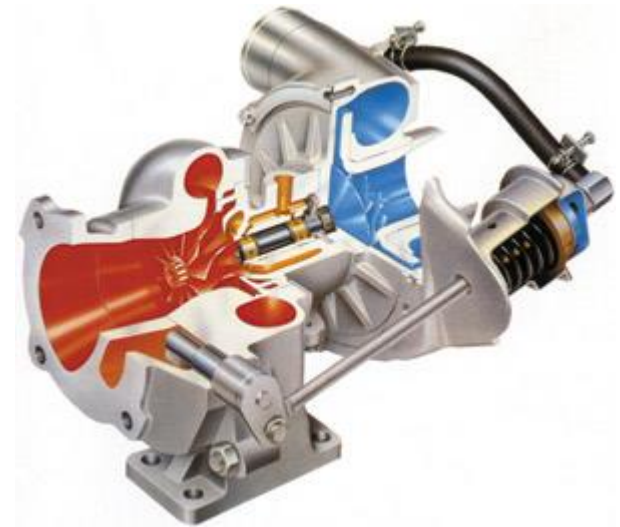
Powertrain Design and Efficiency

Intercoolers



- Compressor selection example
- Compressor outlet temperature calculation
- Intercooler efficiency
- Intercooler design

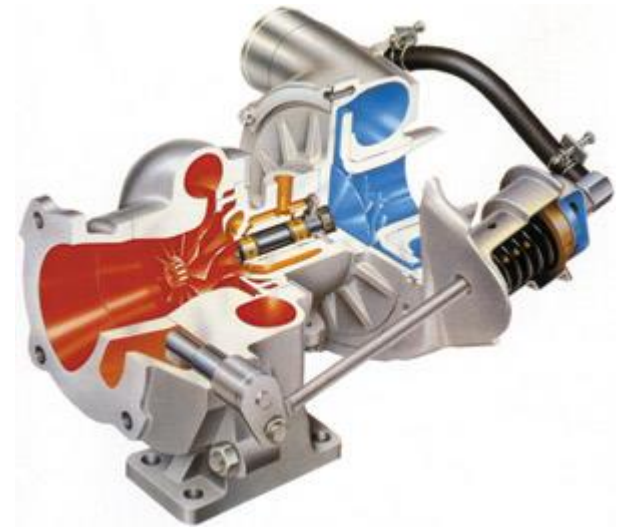
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Compressor example



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- **Example:** A V6 engine has a bore of 73mm and a stroke of 95mm. Its volumetric efficiency in naturally aspirated form is 0.86 (86%), with a red-line at 10000rpm.
 - a) What is its N.A. volumetric flow rate?
 - b) At 11psi of boost, how much airflow must a turbo provide at full throttle (in lb/min)
 - c) Choose a turbo from the 4 options available

Airflow requirements



- For a naturally aspirated engine, the volumetric flow rate of air through the engine is given by:

$$V = \frac{v \times \eta_v \times N}{2 \times 60}$$

where:

V	=	volumetric flow rate (m ³ /s)
v	=	total engine displacement (m ³)
η	=	volumetric efficiency (say 0.85)
N	=	engine speed (rpm)

Airflow requirements



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- For a turbocharged engine, this flow rate must be increased according to the pressure ratio in order to deliver the desired increase in performance, e.g.:

$$V_t = PR \times \frac{v \times \eta_v \times N}{2 \times 60}$$

- Many turbocharger datasheets are in imperial units, where volumetric flow rate is in cubic feet per minute (cfm)
- $1 \text{ m}^3/\text{s} = 2119 \text{ cfm}$
- $1 \text{ cfm} = 0.07 \text{ lb/min}$

Compressor Maps



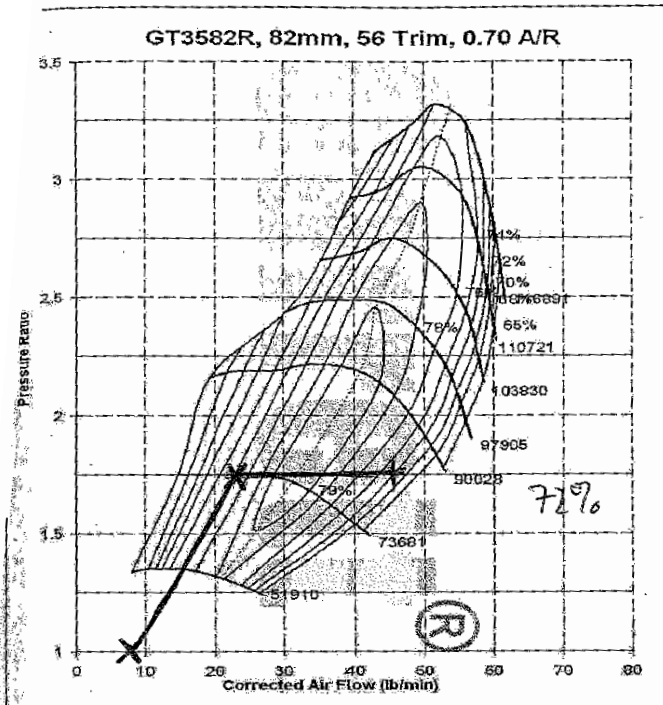
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- Plot the following points on the compressor maps:
 - Maximum air flow at PR
 - i.e. 44.35 lb/min @ PR = 1.75
 - 50% maximum air flow at PR
 - i.e. 22.18 lb/min @ PR = 1.75
 - 20% maximum air flow at PR=1
 - i.e. 8.9 lb/min @ PR = 1.00

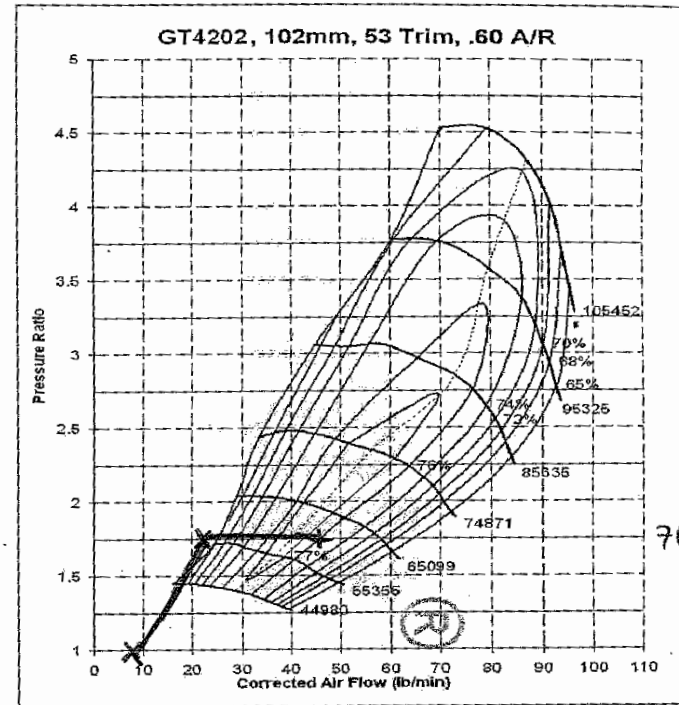
Compressor Maps



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This is the compressor map for the Garrett model GT3582R, part number 714568-2 turbocharger, see current Garrett catalog for turbine housing A/R options. (Courtesy Honeywell Turbo Technologies)

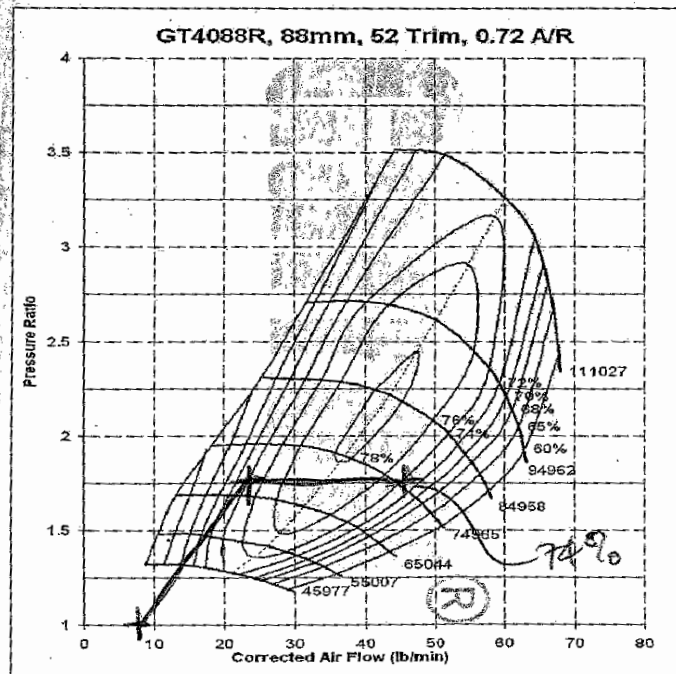


This is the compressor map for the Garrett model GT4202R, use CHRA part number 451888-11 and compressor housing kit 757708-2, see current Garrett catalog for turbine housing A/R options. (Courtesy Honeywell Turbo Technologies)

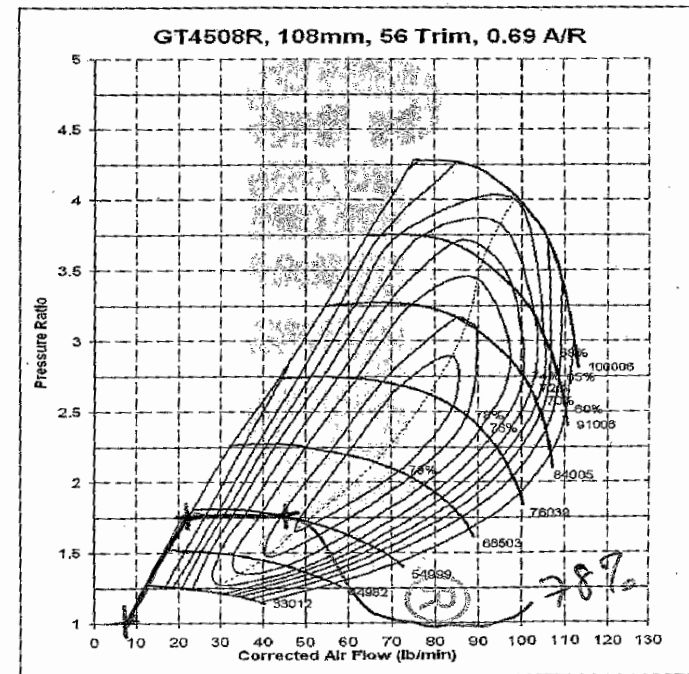
Compressor Maps



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This is the compressor map for the Garrett model GT4088R, part number 751470-2 turbocharger, see current Garrett catalog for turbine housing A/R options. (Courtesy Honeywell Turbo Technologies)

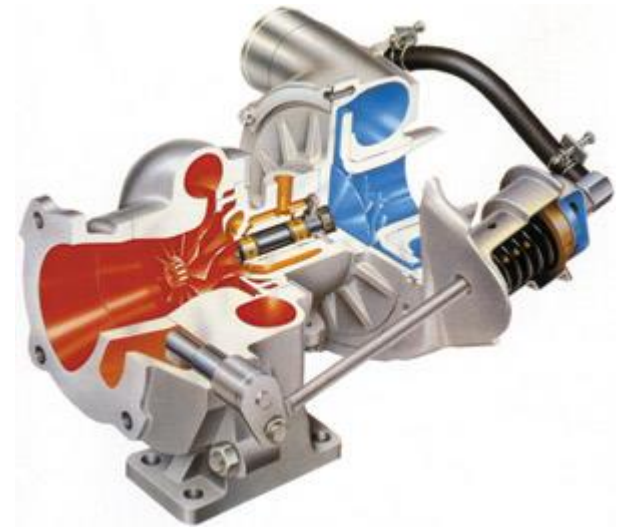


This is the compressor map for the Garrett model GT4508R, part number 742581-4 turbocharger, see current Garrett catalog for turbine housing A/R options. (Courtesy Honeywell Turbo Technologies)



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Compressor outlet temp



- We defined compressor efficiency as being the ratio of calculated to actual temperature rise of the compressed intake charge
- The theoretical discharge temperature is given by consideration of an adiabatic (no heat loss) compression:

$$T_{out} = PR^{0.28} \times T_{in}$$

- Where T_{in} is the inlet temperature (in kelvin)
PR = pressure ratio

Compressor outlet temp



- Thus compressor efficiency, η_c is:

$$\eta_c = \frac{\left(PR^{0.28} \times T_{in} \right) - T_{in}}{\text{Actual Temp Rise}}$$

- So if we know the compressor efficiency and inlet temperature, we can calculate the actual temperature rise:

$$\text{Actual Temp Rise} = \frac{\left(PR^{0.28} \times T_{in} \right) - T_{in}}{\eta_c}$$

Compressor outlet temp



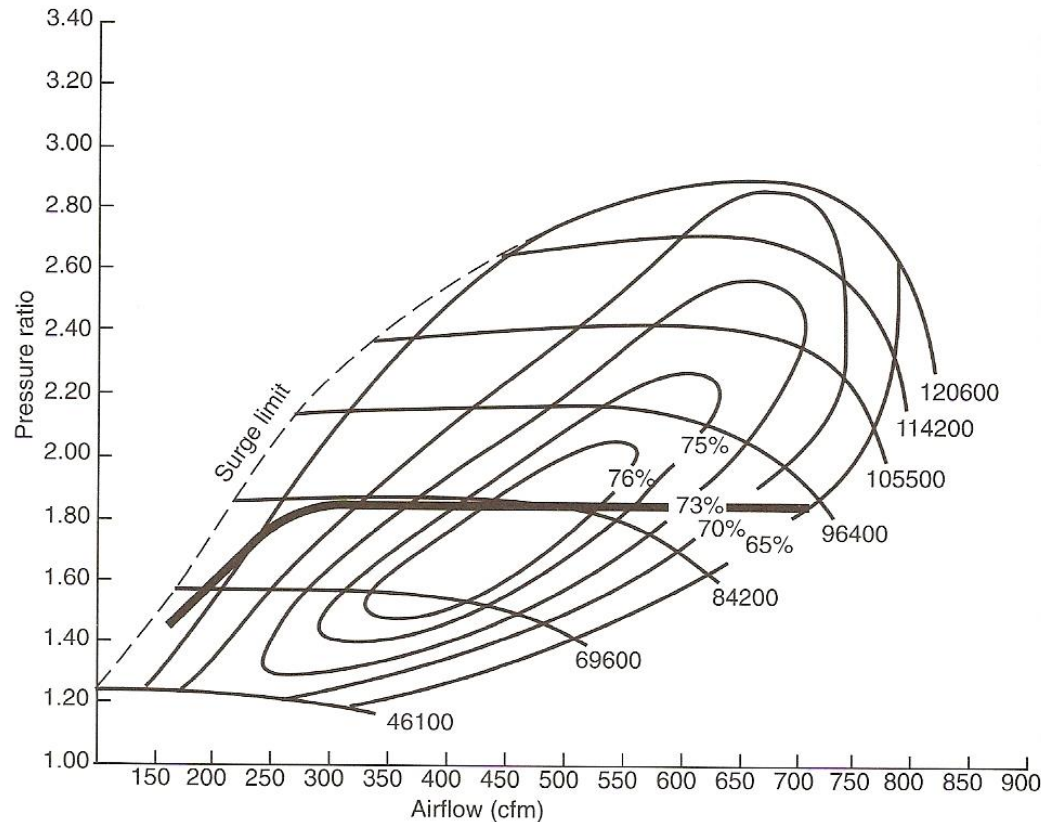
- **Example:** The ambient temperature is 27°C. If a turbocharger has a pressure ratio of 1.36, what is the compressor outlet temperature, if the compressor is operating at an efficiency of 0.76?

$$\text{Actual Temp Rise} = \frac{(PR^{0.28} \times T_{in}) - T_{in}}{\eta_c}$$

Compressor outlet temp



- However, going back to our compressor maps, we can see that the turbocharger operates under a range of efficiencies as the engine speed (and hence air flow) changes.

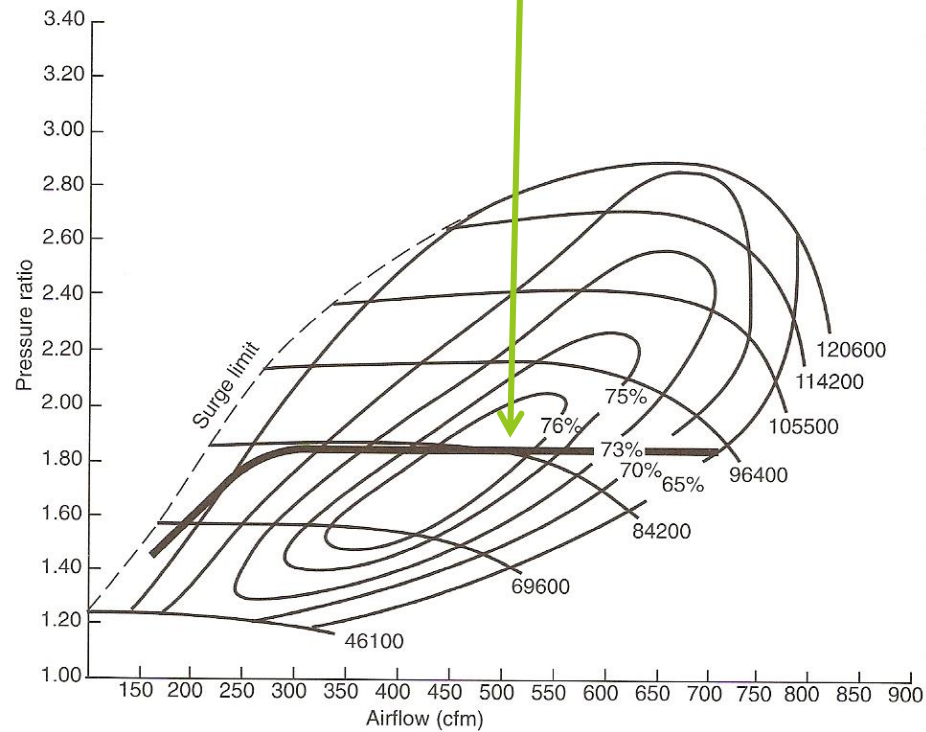


Compressor outlet temp



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- At max efficiency, this turbo is 76% efficient.

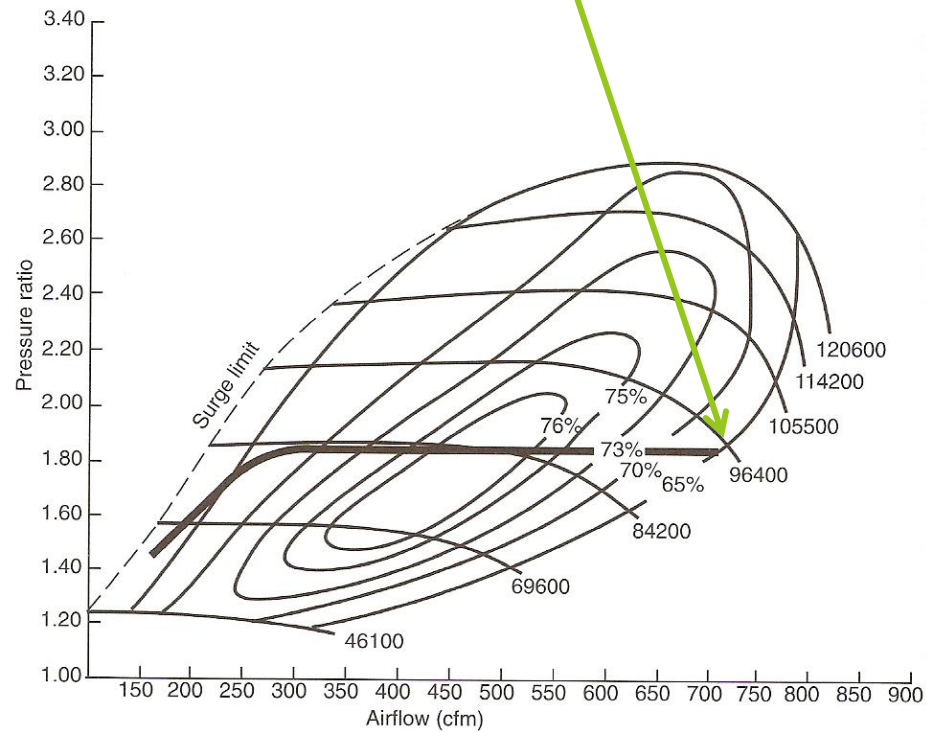


Compressor outlet temp



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- At max load, this turbo is 65% efficient.



Compressor outlet temp



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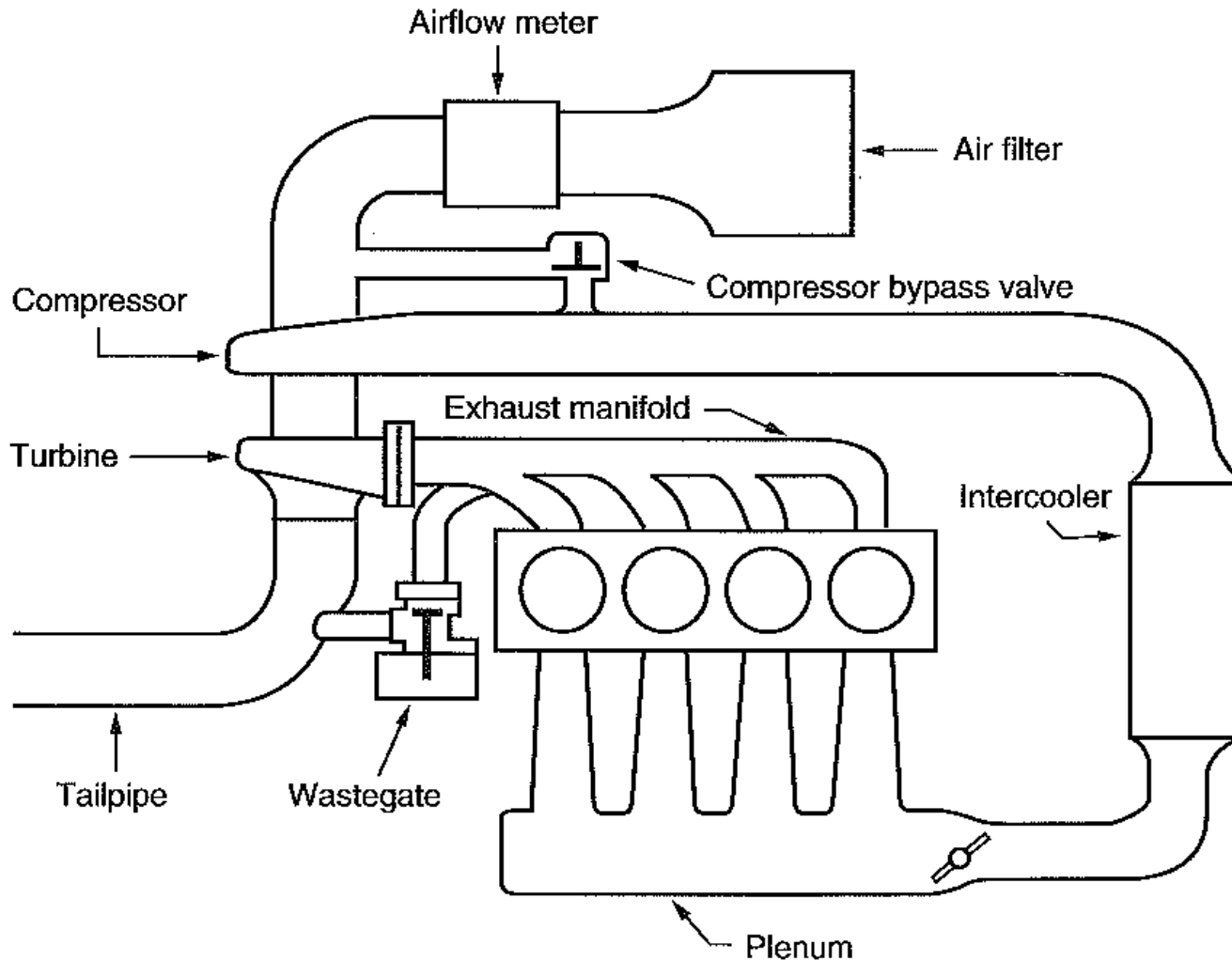
- Thus we can work out the temperature rise under maximum load conditions and at maximum efficiency conditions
- The rise at maximum load conditions will be higher than that at maximum efficiency
- We can use an intercooler to reduce the temperature rise



Compressor outlet temp



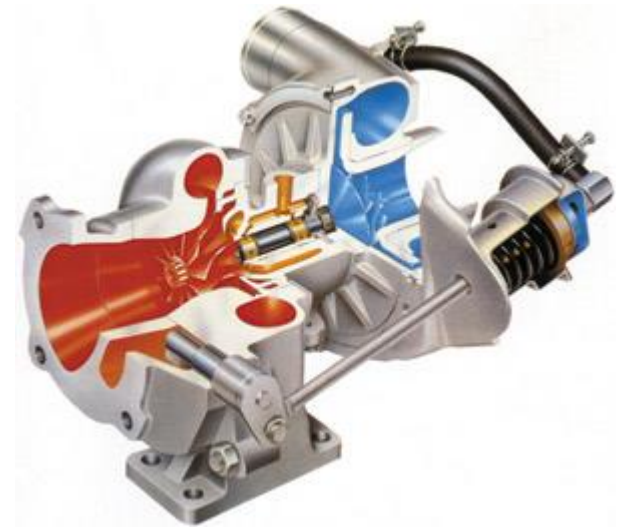
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- **Intercooler efficiency**
- Intercooler design

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Intercooler efficiency



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- This is defined as the ratio of the amount of heat removed by the intercooler to the amount of heat added by the turbo
- So if an intercooler is 60% efficient, it will remove 60% of the temperature rise which the compressor produces

$$\eta_i = \frac{T_{co} - T_{io}}{T_{co} - T_a}$$

where T_{co} = compressor outlet temp

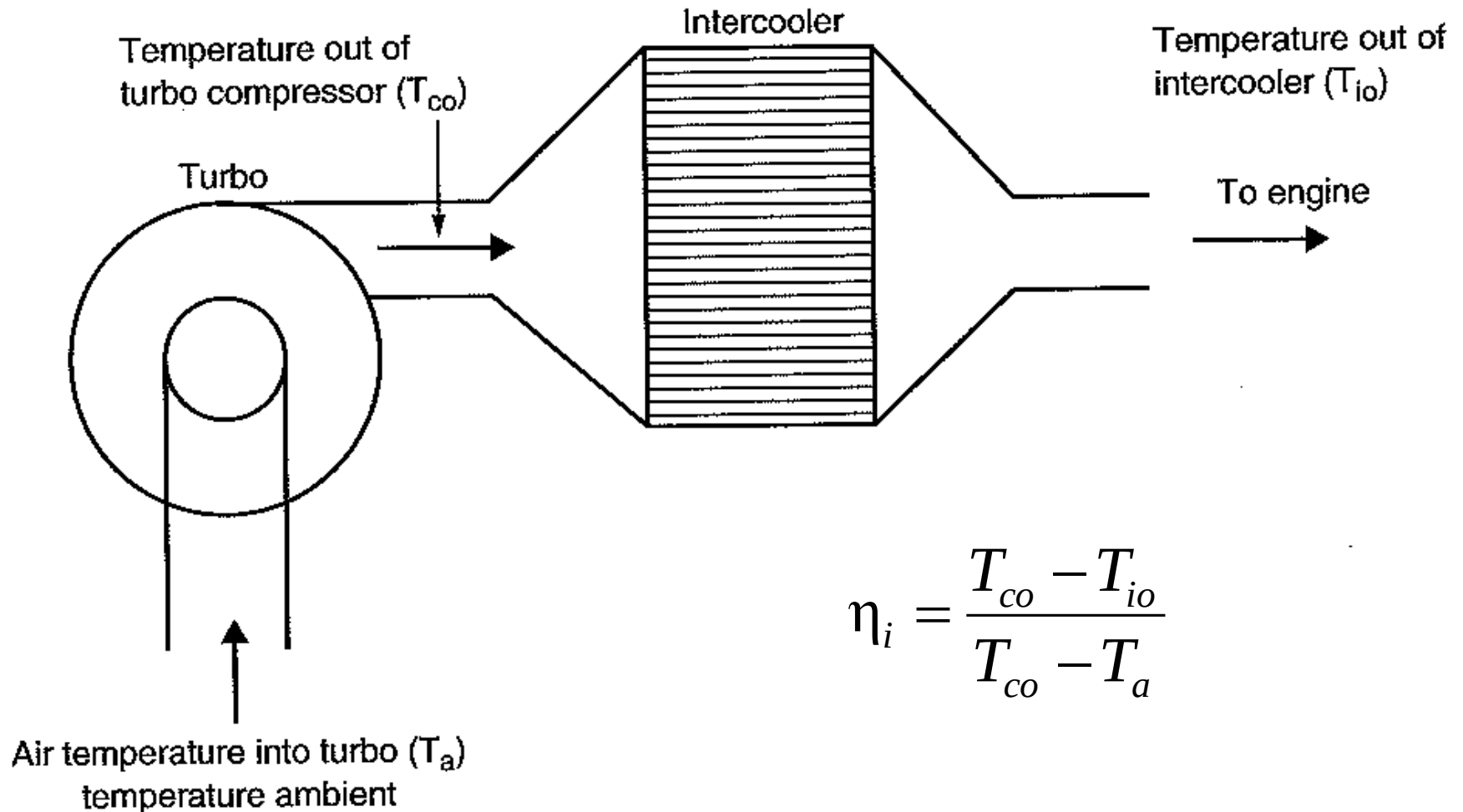
T_{io} = intercooler outlet temp

T_a = ambient (inlet) temp

Intercooler efficiency



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Intercooler efficiency



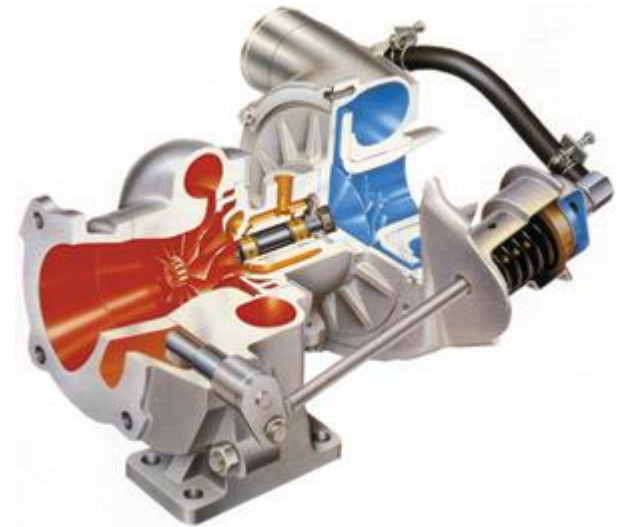
- **Example:** If the system previously analysed (with $T_{co} = 62.5^{\circ}\text{C}$, $T_a = 27^{\circ}\text{C}$) is fitted with an intercooler which is 60% efficient, what is the outlet temperature from the intercooler?

$$\eta_i = \frac{T_{co} - T_{io}}{T_{co} - T_a}$$



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Intercooler design



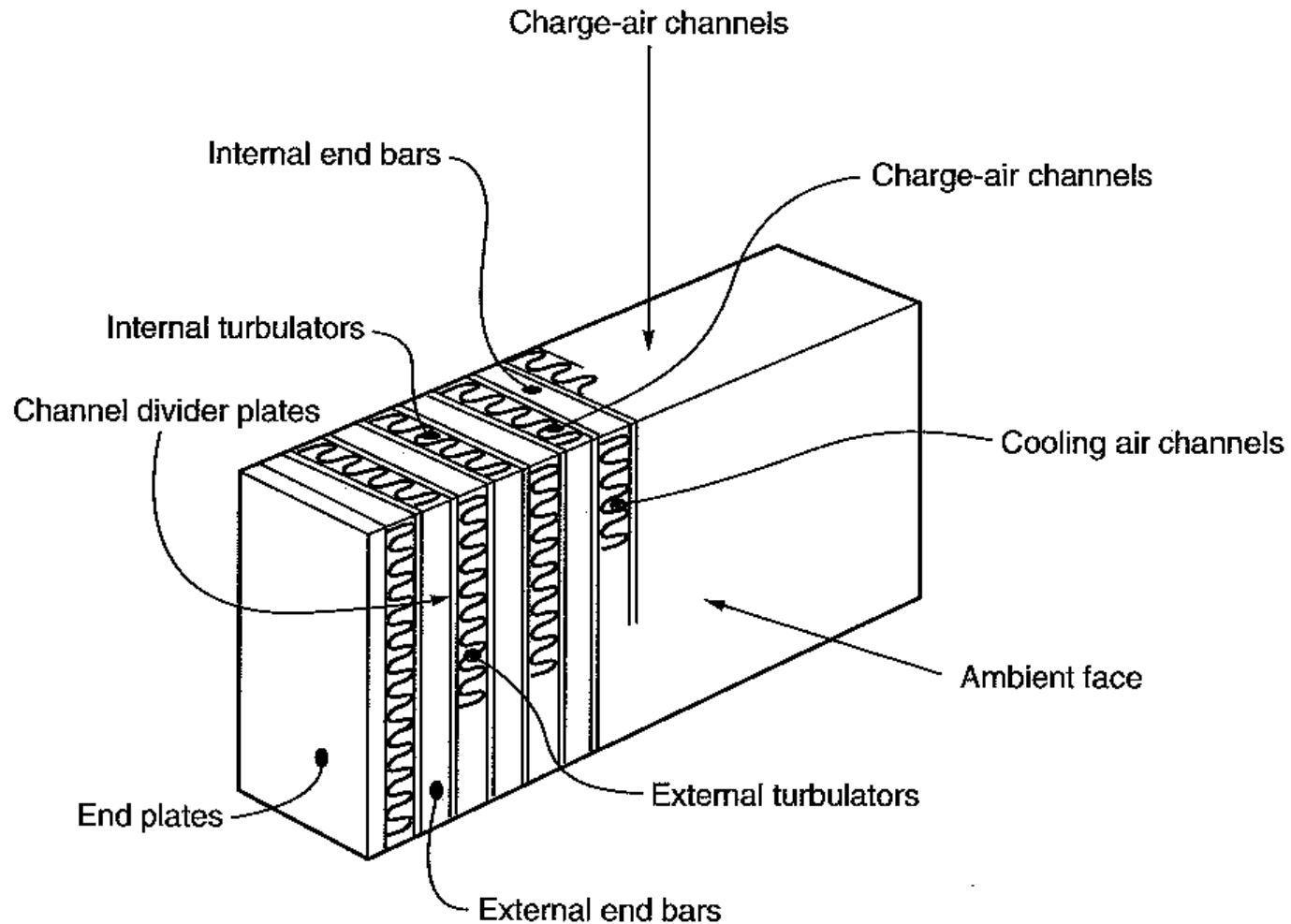
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- Essentially an air / air or air / water heat exchanger
- Air to air systems
 - Are simpler
 - Greater efficiency at high speeds
 - Greater reliability
 - Lower maintenance
 - Lower costs
- Air to water systems
 - Better thermal efficiency at low speeds
 - Smaller and more compact

Intercooler design



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Intercooler design



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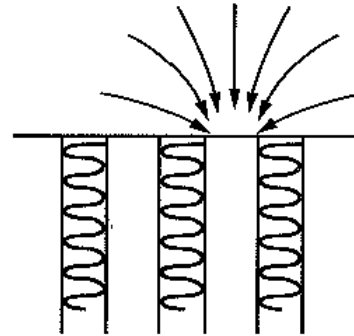
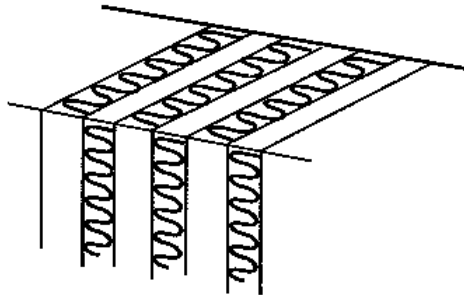
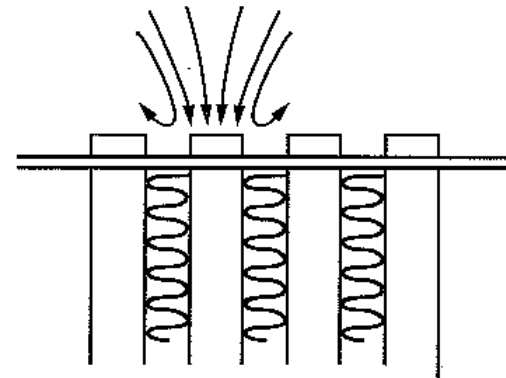
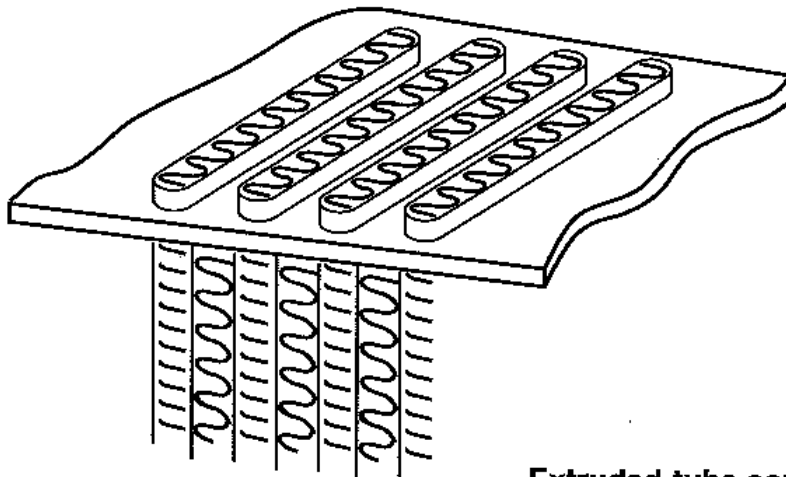


Plate-and-shell core



Extruded-tube core

Intercooler design



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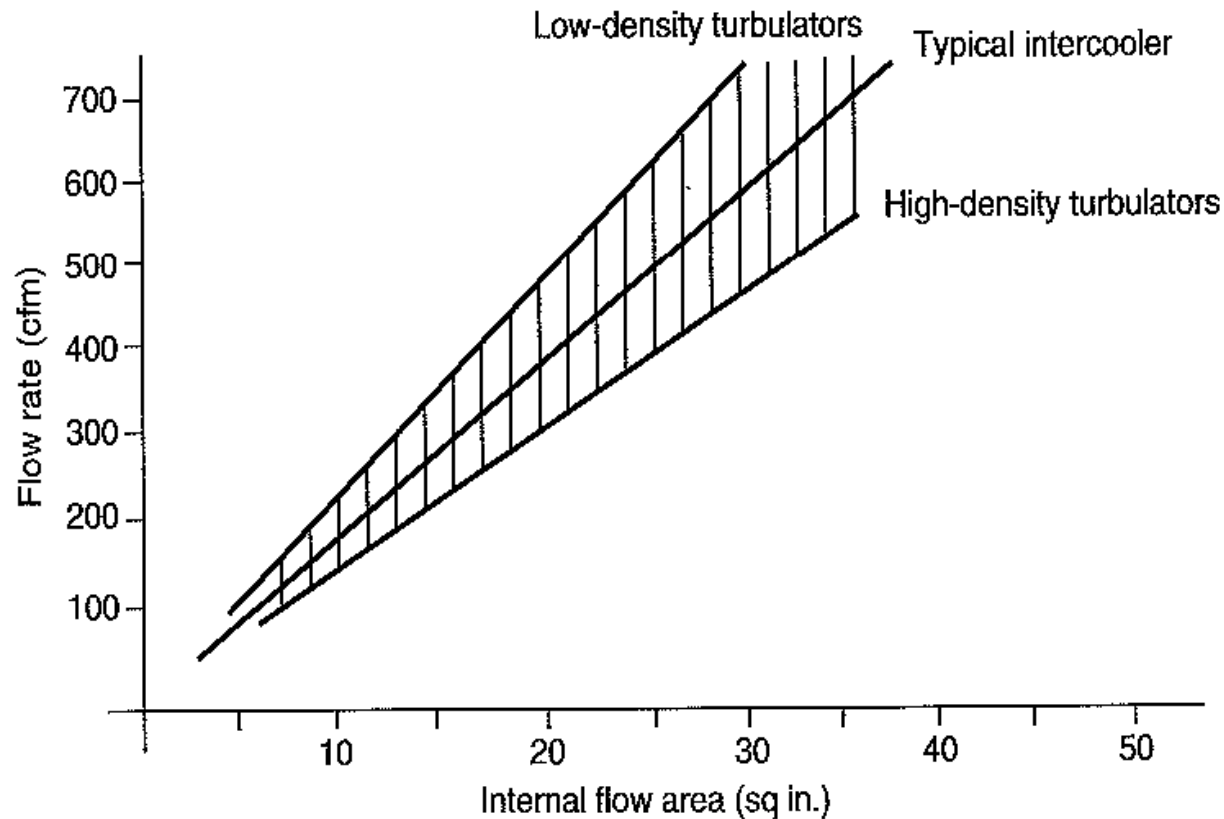
- **Plate and shell** type offers less flow resistance
- **Extruded tube** type is generally more thermally efficient
- **Turbulators** make the flow turbulent through the intercooler core, promoting heat exchange
- However, they also create drag (pressure drop) and so a careful balance must be found between pressure drop and heat exchange

Intercooler design



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- To size an intercooler, the following graph can be used to find the relationship between internal flow area and air-flow requirements

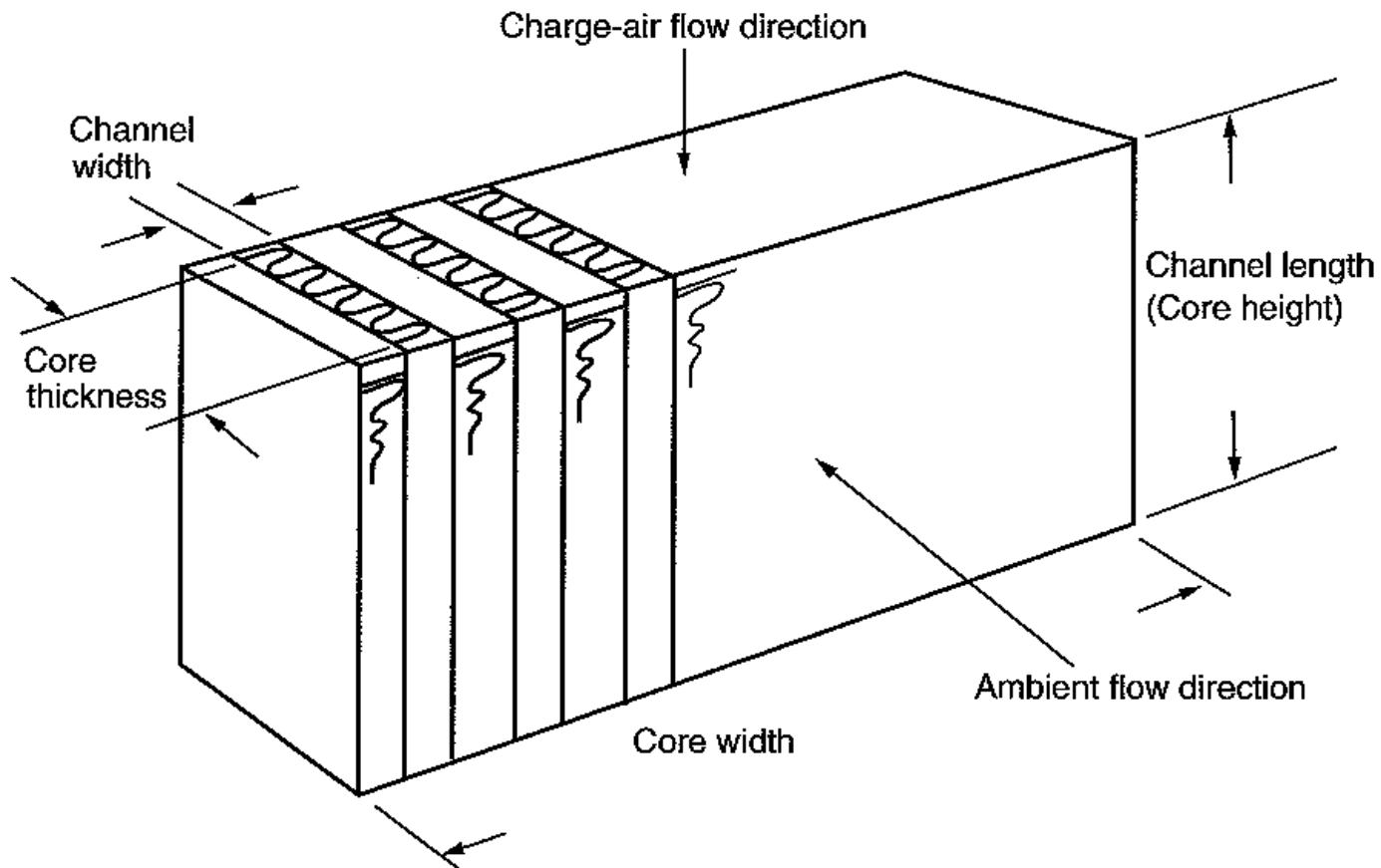


Intercooler design



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- Internal flow area is the channel length x channel width x number of channels



Intercooler design



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- For a typical intercooler, around 45% of the charge air face is available for entry into the tubes.
- So the required internal area must be factored up by this 45% factor.
- i.e. If an internal area of 25 sq.inches is required, the area of the charge air face is:

$$25/0.45 = 56 \text{ sq. Inches}$$

- This area is given by the core thickness x core width