The treatment of the throttling effect in incompressible 1D flow solvers

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The throttling effect of a tunnel fire

- Fire increases the aerodynamic resistance of the tunnel
- Important for ventilation system design
- Various treatments in different software packages
- Limited literature available
- Objectives
  - identify mechanisms of throttling effect
  - understand how they are modelled

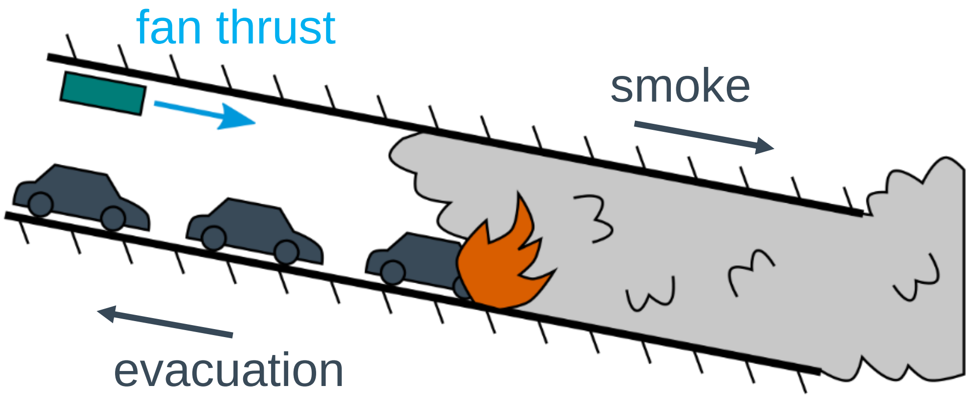
Outline

- Overview of throttling effect
- Consider some throttling mechanisms
  - Wall friction & local losses
  - Momentum change at fire
- Demonstration
  - User-defined fire pressure drop (IDA Tunnel 1.1)

Tunnel fire

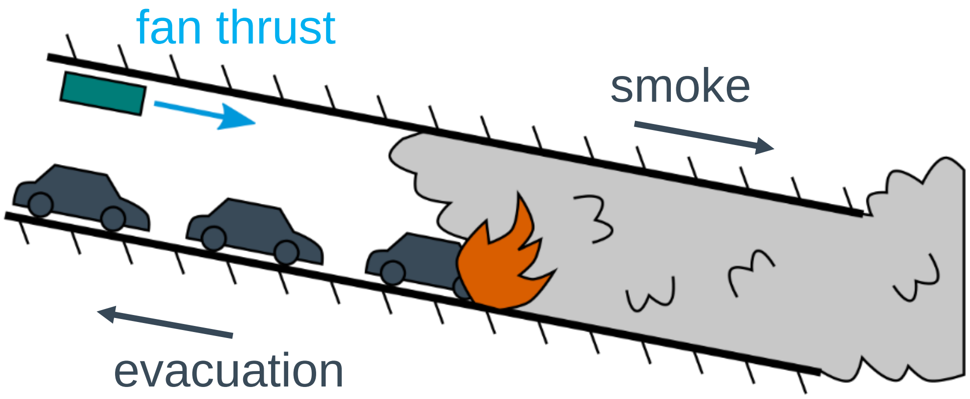
Longitudinal ventilation system

- Self-rescue
- Fire-fighting



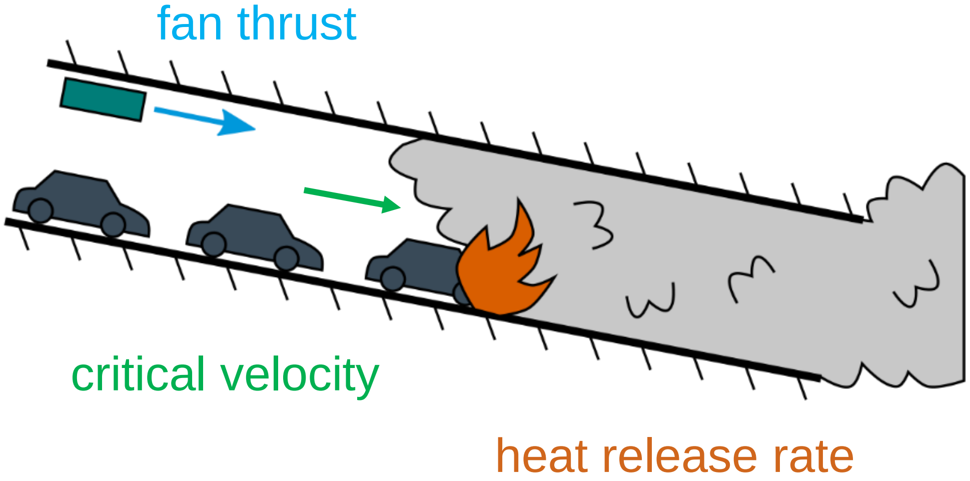
Ventilation system design

- Achieve critical velocity
- Overcome aerodynamic resistance, e.g:
  - buoyancy
  - vehicle drag
  - wall friction & local losses
  - momentum change
  - portal pressure difference
- Iterative numerical method



System resistance

Some losses are temperature-dependent



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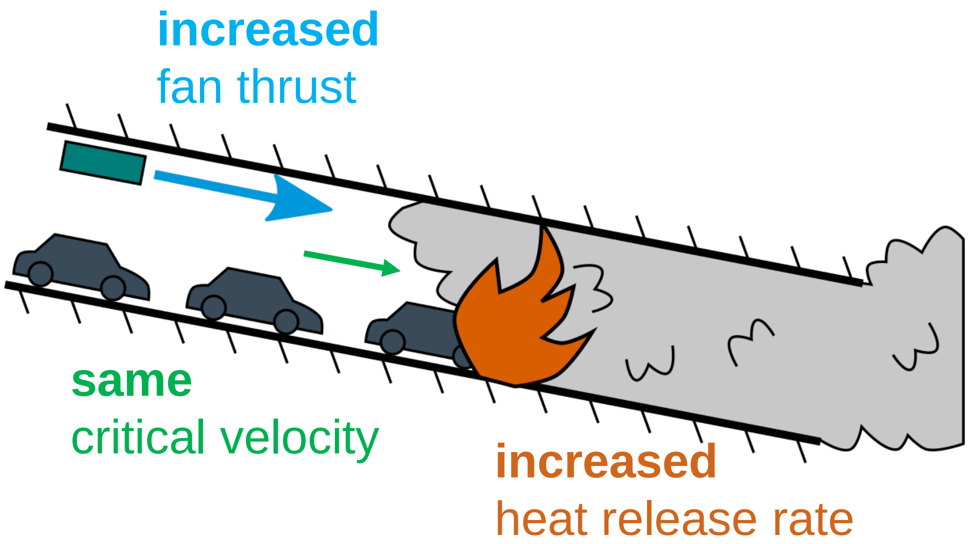

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System resistance

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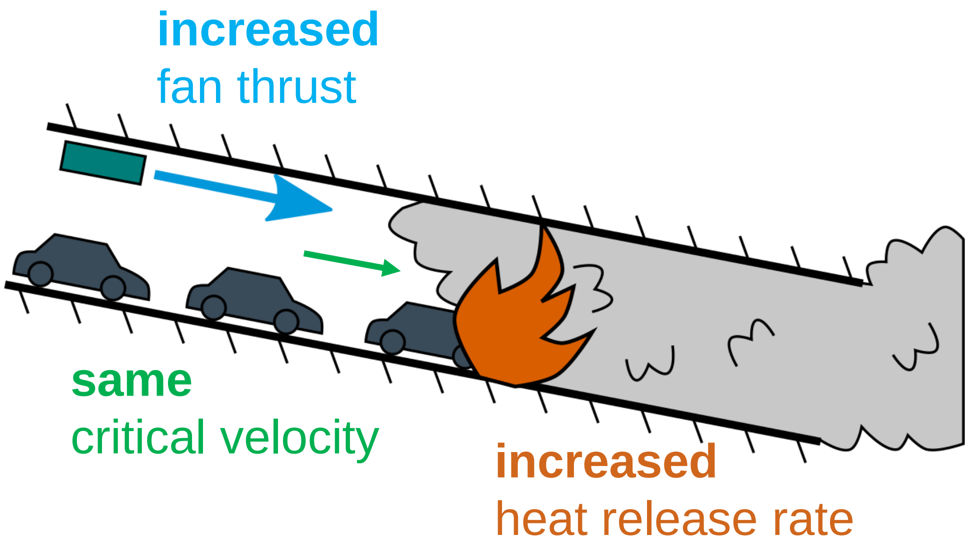
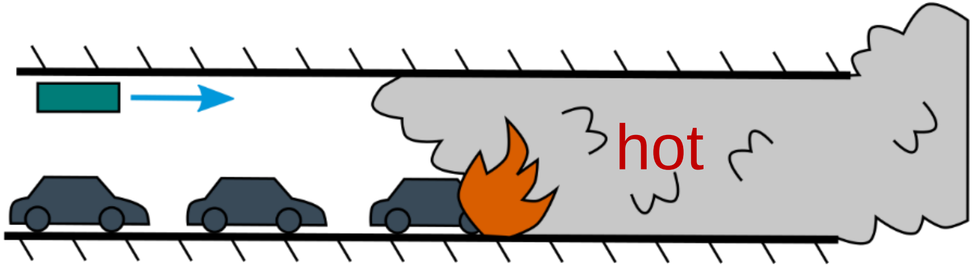
Some losses are temperature-dependent

- buoyancy
- wall friction & local losses
- momentum change



Wall friction & local losses



Losses depend on dynamic pressure

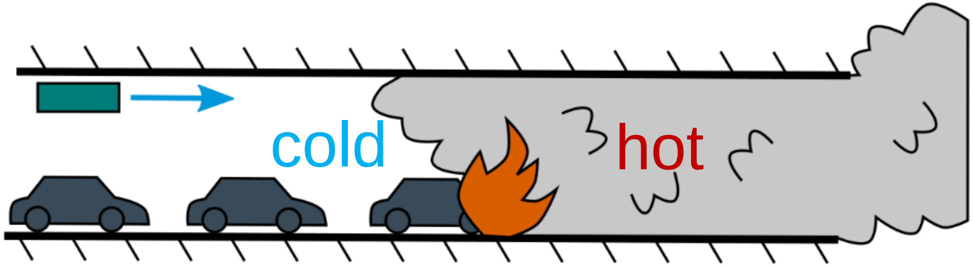
$$\Delta p_{\mathrm{friction}} = \frac{\lambda L}{D} \times \frac{1}{2}\rho u^2 \qquad \Delta p_{\mathrm{exit}} = K_{\mathrm{exit}} \times \frac{1}{2}\rho u^2$$

Dynamic pressure is proportional to temperature

$$\frac{1}{2}\rho u^2 \propto T$$

Flow is compressible!

Wall friction & local losses



Ideal Gas Law

$$\rho = \frac{p}{RT}$$

$$\rho_h = \rho_c \frac{T_c}{T_h}$$

Continuity

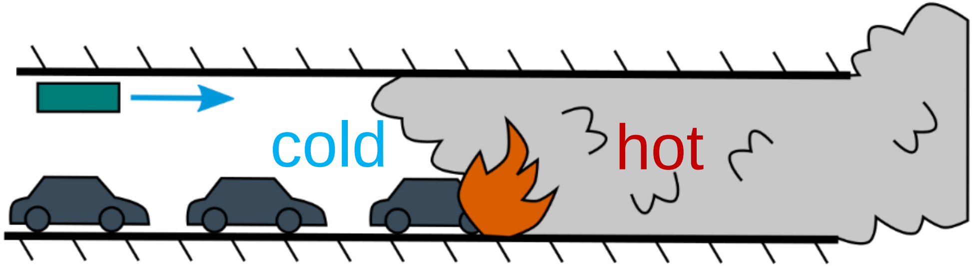
$$\dot{m} = \rho u A = \text{const.}$$

$$u_h^2 = u_c^2 \frac{T_h^2}{T_c^2}$$

Corrected dynamic pressure

$$\frac{1}{2}\rho_h u_h^2 = \frac{1}{2}\rho_c u_c^2 \times \frac{T_h}{T_c}$$

Wall friction & local losses



Pressure losses now expressed in terms of known variables,

$$\rho_c, u_c, T_h$$

$$\Delta p_{\text{friction}} = \frac{\lambda L}{D} \times \frac{1}{2} \rho_c u_c^2 \frac{T_h}{T_c}$$

$$\Delta p_{\text{exit}} = K_{\text{exit}} \times \frac{1}{2} \rho_c u_c^2 \frac{T_h}{T_c}$$

Pressure loss at fire

Momentum change
(Hwang & Chaiken, 1978)

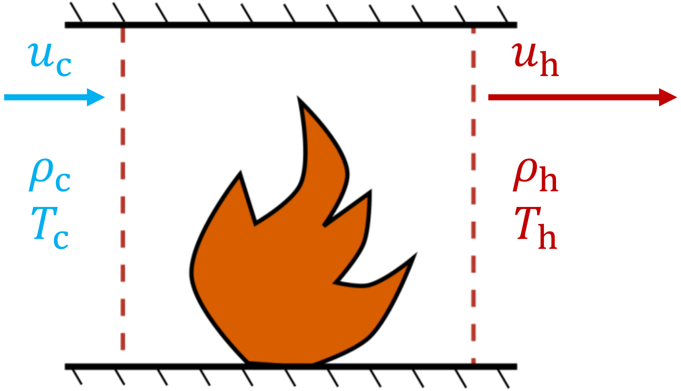
$$\Sigma F_{\mathrm{CV}} = \dot{m}(u_{\mathrm{c}} - u_{\mathrm{h}})$$

$$u_{\mathrm{h}} = u_{\mathrm{c}} \frac{T_{\mathrm{h}}}{T_{\mathrm{c}}}$$

$$\Delta p_{\mathrm{fire}} = \rho_{\mathrm{c}} u_{\mathrm{c}}^2 \left(1 - \frac{T_{\mathrm{h}}}{T_{\mathrm{c}}}\right)$$

'HC78'

1D control volume

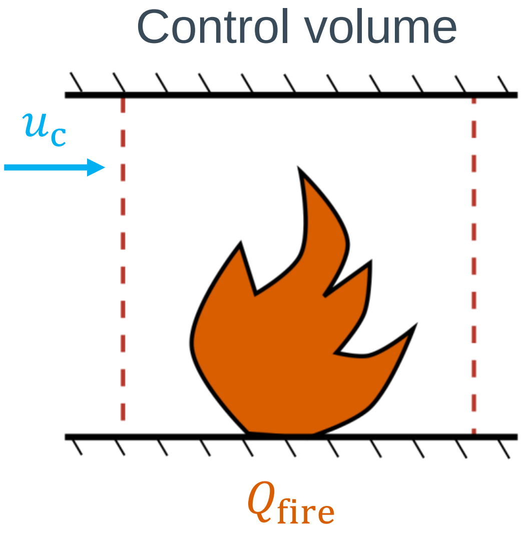


Pressure loss at fire

Empirical formula via 3D CFD
(Dutrieue & Jacques, 2006)

$$\Delta p_{\mathrm{fire}} = \frac{Q_{\mathrm{fire}}^{0.8} u_{\mathrm{c}}^{1.5}}{D^{1.5}} C$$

'DJ06'



Implementation

Some flow solvers require user input

- e.g. IDA Tunnel – general fire pressure loss

$$C_{\mathrm{fire}} = \frac{\Delta p_{\mathrm{fire}}}{Q_{\mathrm{fire}}}$$

Proposed use of IDA Tunnel

1. Calculate Δp_{fire} manually
    - $\Delta p = 0$
    - HC78 or DJ06
2. Calculate C_{fire} manually
    - Input to IDA Tunnel
3. IDA Tunnel simulation
    - Solve for $u_{\mathrm{c}}, T_{\mathrm{h}}$

iterate

Implementation

Some flow solvers require user input

- e.g. IDA Tunnel – general fire pressure loss

$$C_{\mathrm{fire}} = \frac{\Delta p_{\mathrm{fire}}}{Q_{\mathrm{fire}}}$$

Some flow solvers do not require user input

- e.g. SES v4.1 solves HC78 momentum change

Proposed use of IDA Tunnel

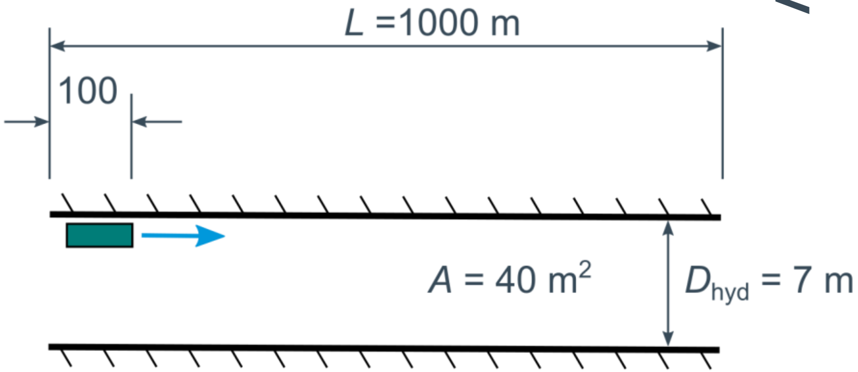
1. Calculate Δp_{fire} manually
   - $\Delta p = 0$
   - HC78 or DJ06
2. Calculate C_{fire} manually
   - Input to IDA Tunnel
3. IDA Tunnel simulation
   - Solve for $u_{\mathrm{c}}, T_{\mathrm{h}}$

iterate

Demonstration

Trivial case

- Verify agreement of IDA Tunnel 1.1 and SES v4.1
  - verify jet fan
  - verify wall friction



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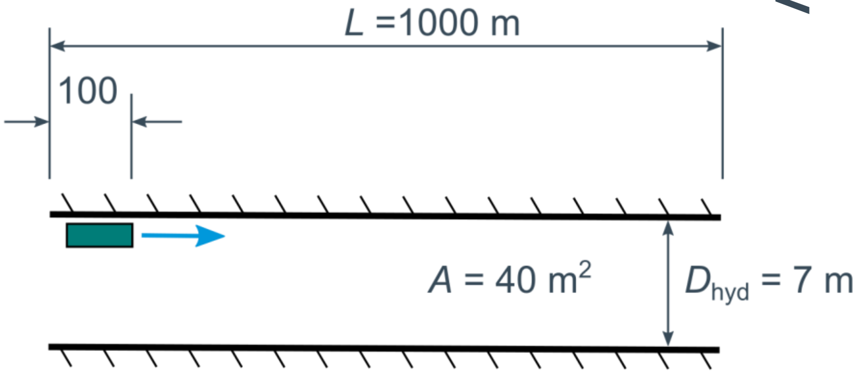


Results

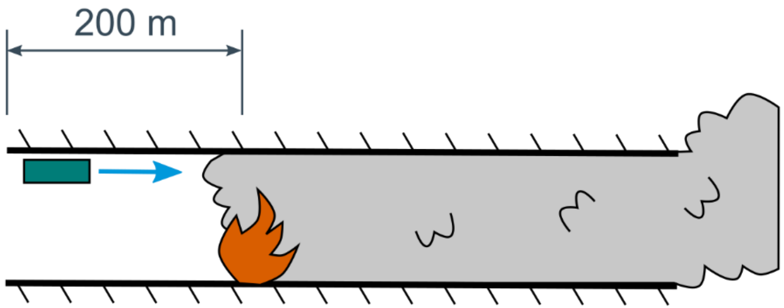
- Good agreement

Solver	u [m/s]	Δp_0 [Pa]
IDA Tunnel	3.702	19.704
SES v4.1	3.701	19.670

Demonstration

Fire pressure loss in IDA Tunnel

- Test models
  - $\Delta p_{\text{fire}} = 0$ Pa
  - $\Delta p_{\text{fire}} =$ DJ06 (empirical)
  - $\Delta p_{\text{fire}} =$ HC78 (momentum change)
- Vary fire size



$Q_{\text{fire}} = 20\ \text{MW}$

Demonstration

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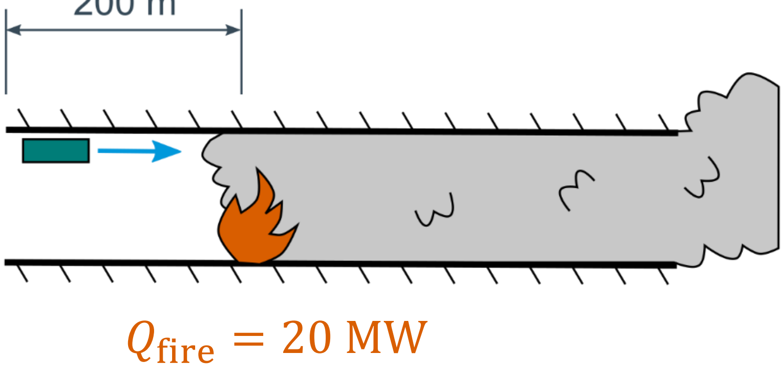
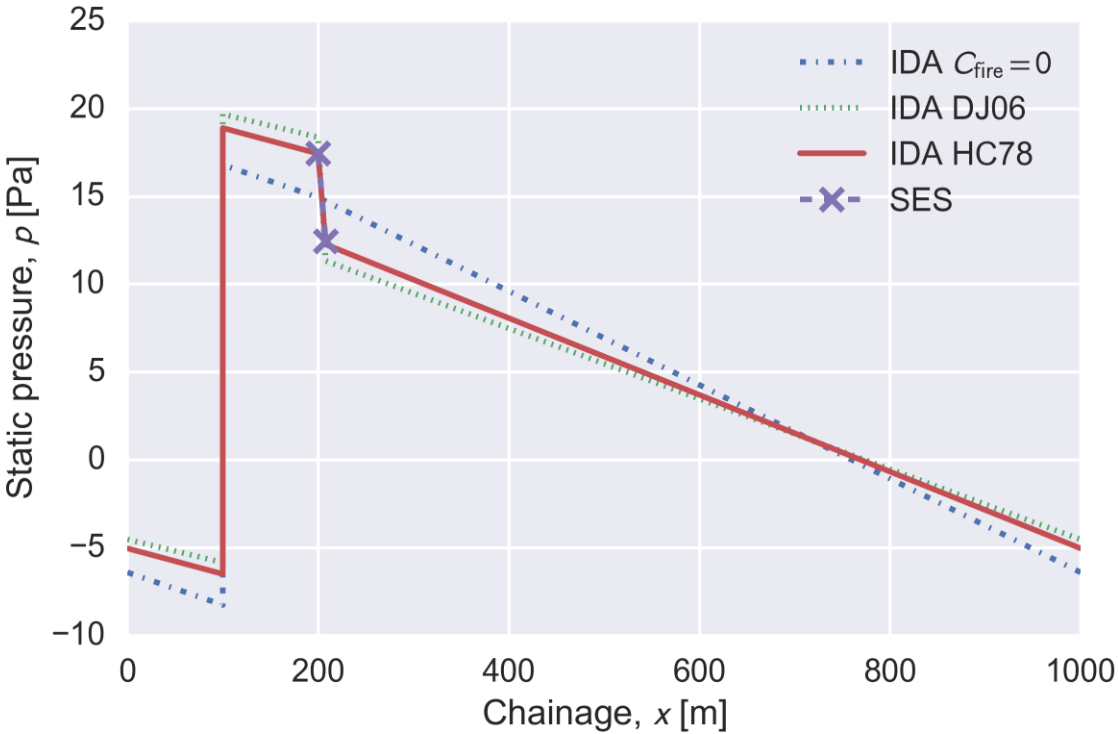
Assumptions

(to isolate fire pressure drop)

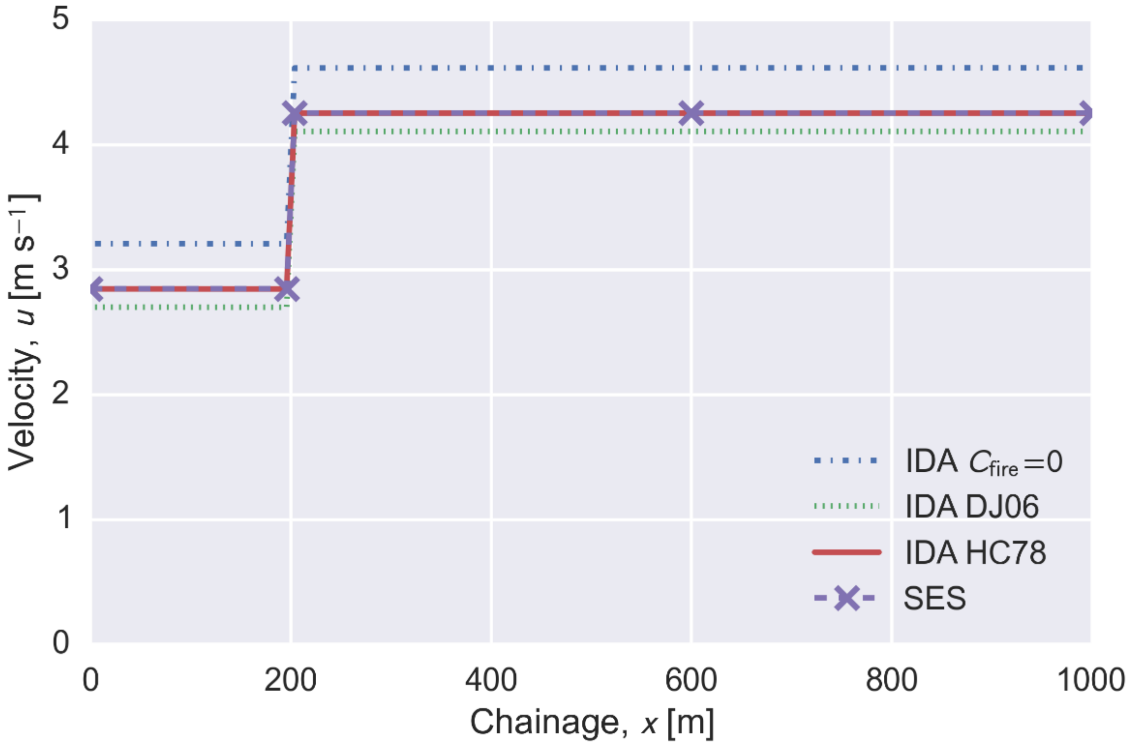
- No wall heat transfer
- No entry/exit loss



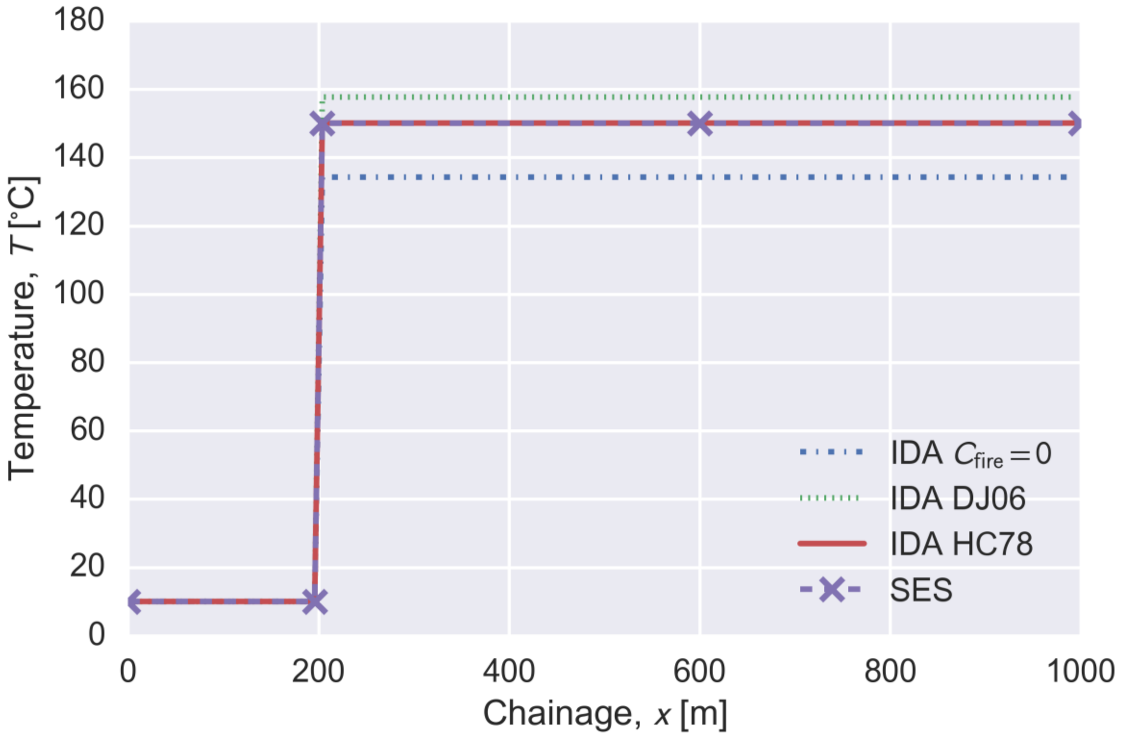
Demonstration - pressure



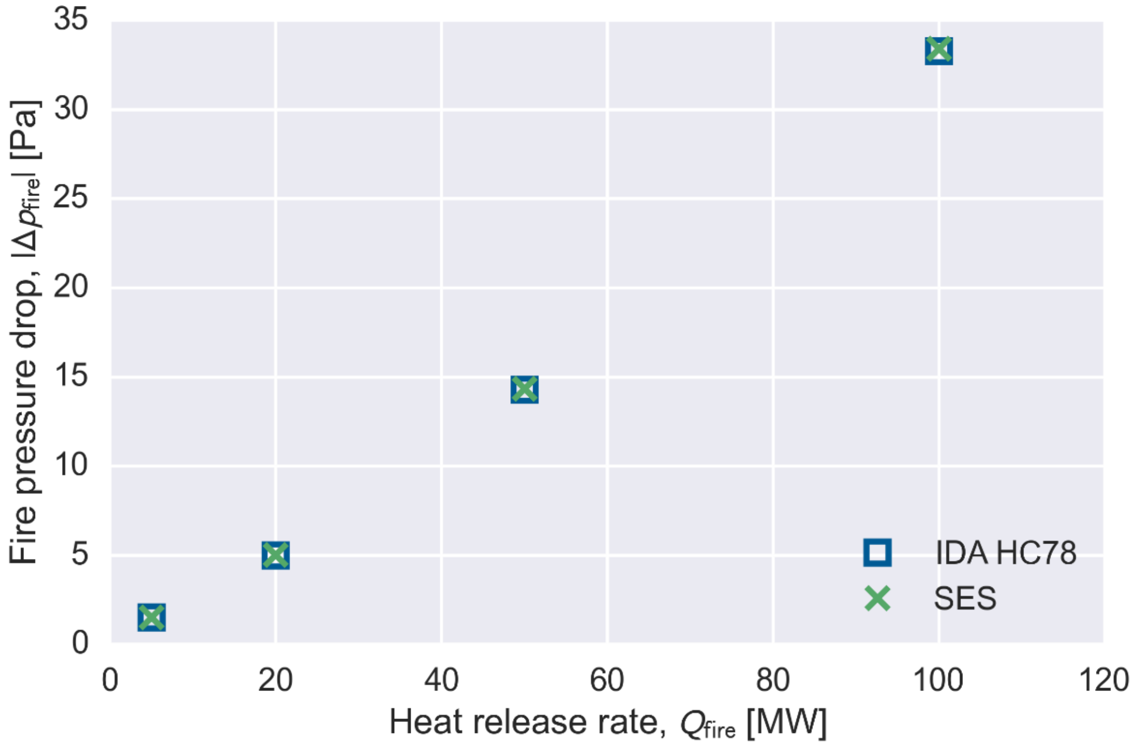
Demonstration - velocity



Demonstration - temperature



Demonstration – vary fire size



Conclusions

Overview of throttling effect

- Focussed on
  - wall friction & local losses
  - momentum change

Suggested method for user-defined momentum change

Demonstrated method using IDA Tunnel

Thank you

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