FACULTY OF ENGINEERING
AND ARCHITECTURE

DEPARTMENT FLOW, HEAT AND COMBUSTION MECHANICS
TRANSPORT TECHNOLOGY RESEARCH GROUP

EVALUATION OF WALL HEAT FLUX MODELS FOR CFD SIMULATIONS OF AN INTERNAL COMBUSTION ENGINE UNDER BOTH MOTORED AND HCCI OPERATION

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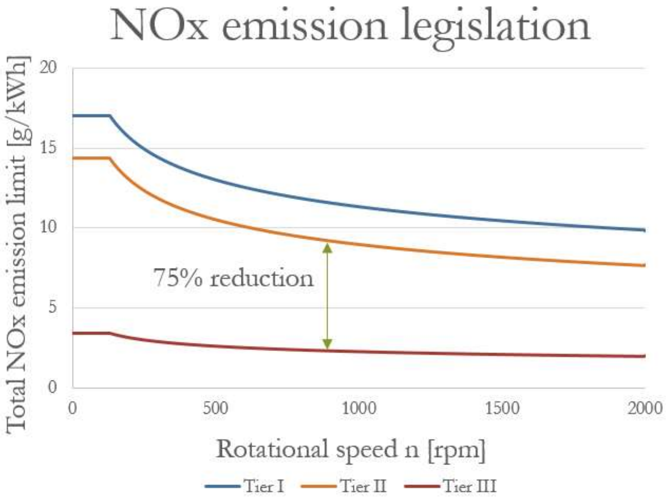
PRETREF

INTRODUCTION

IMO: International Maritime Organization



INTRODUCTION

Dual-Fuel Internal Combustion Engine

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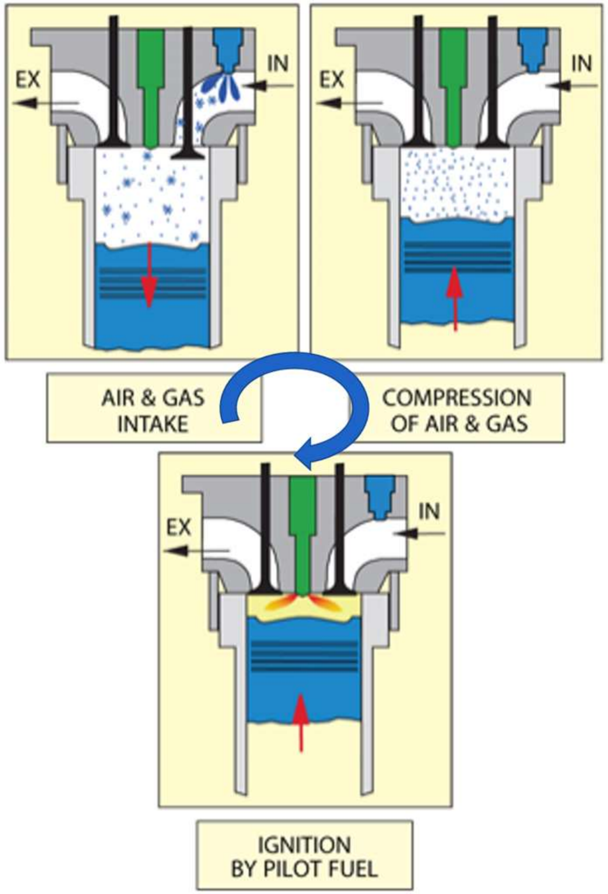

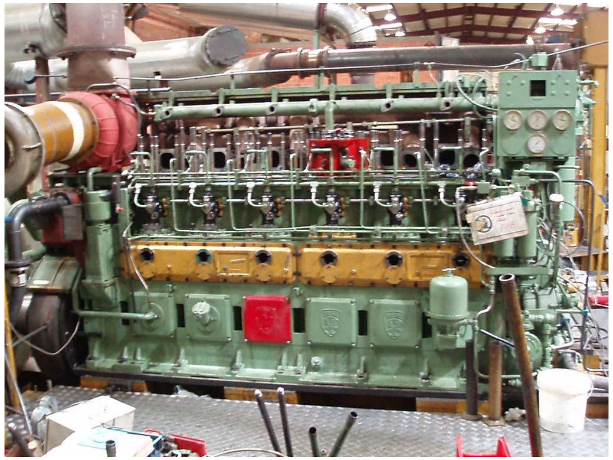

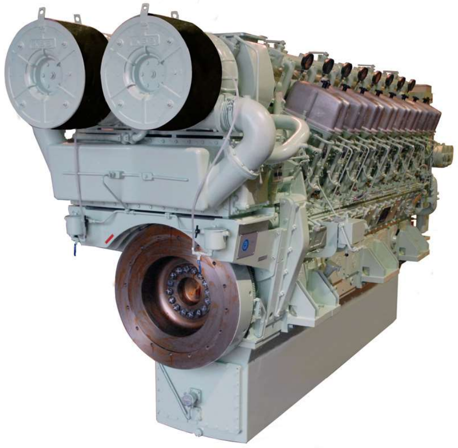

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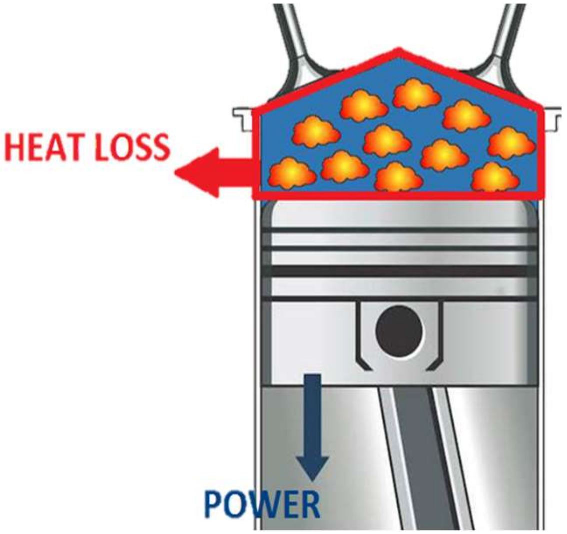
GOALS

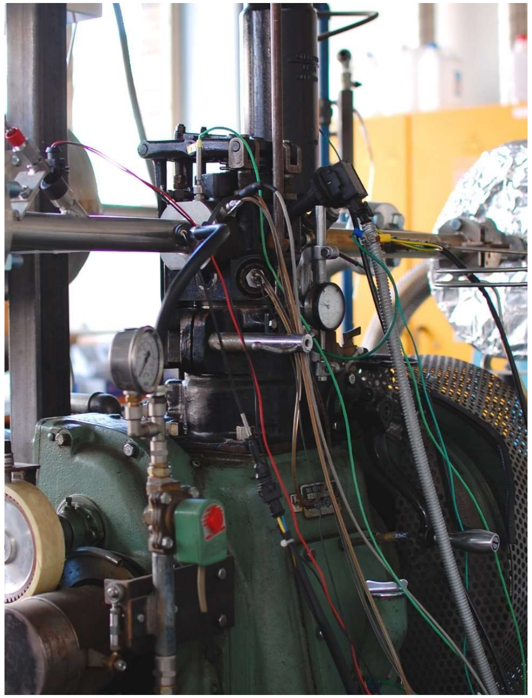
- Develop CFD tool to support the development of Dual-Fuel ICE

- Complex: Diesel spray igniting the premixed fuel-air mixture, that burns through flame propagation

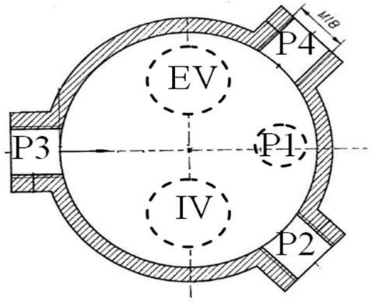
- First focus on pieces of the puzzle:
  - Cold flow, in-cylinder analysis
  - Combustion simulations + in-cylinder heat transfer
  - Simulation of a (combusting) marine diesel spray
  - Dual fuel combustion + flame propagation versus extinction

IN-CYLINDER HEAT TRANSFER





- Evaluate heat flux through engine walls
- Analyse predictable CFD wall models
    - Currently being done based on old engine experiments
- Combine in-house experiments with CFD



WALL HEAT FLUX MODELS

- Apply assumptions and simplify thin shear-layer energy eq.

$$\rho c_p \left[\frac{\partial \bar{T}}{\partial t} + \bar{u_x} \frac{\partial \bar{T}}{\partial x} + \bar{u_y} \frac{\partial \bar{T}}{\partial y} \right] = \frac{\partial \bar{p_0}}{\partial t} + \frac{\partial}{\partial y} \left[(\bar{\lambda} + \lambda_t) \frac{\partial \bar{T}}{\partial y} \right] + \dot{Q}$$

➔ $T^+ = \frac{1}{0.4767} \left[\ln \left(y^+ + \frac{1}{\mathrm{Pr}\ 0.4767} \right) - \ln (40 + \frac{1}{\mathrm{Pr}\ 0.4767}) \right] + 10.2384 + P^+ \left(\frac{y^+ - 40 + 1 \quad .31(0.476 \qquad /Pr)}{0.4767 \quad /Pr} \right)$

With $T^+ = \frac{\rho u_t c_p T}{q_w} \ln(\frac{T_w}{T})$, $P^+ = \frac{\left(\frac{dP}{dt}\right) v}{q_w u_t}$ (Rakopoulos et al.)

➔ $$q_w = \frac{\rho c_p u_\tau T\, ln(T_w/T) - \frac{dP}{dt} \frac{\nu}{u_\tau} \left(\frac{y^+ - 40}{0.4767 + \frac{1}{Pr}} + 117.31 \right)}{\frac{1}{0.4767} \left[ln(y^+ + \frac{1}{0.4767 Pr}) - ln(40 + \frac{1}{0.4767 Pr}) \right] + 10.2384}$$

CONVECTIVE HEAT FLUX MODEL

- Calculate heat flux based on the convective law

$$q_w = h\,(T_{gas} - T_w)$$

➔Model convective coefficient *h* by Pohlhausen equation

$$\frac{hL}{k} = Nu = a\,Re^b\,Pr^c$$

- Characteristic length L = Bore
- Characteristic velocity U = $\sqrt{2k}$
- Constants a, b & c = 0.15, 0.8 & 0

[S. Broekaert. “A Study of the Heat Transfer in Low Temperature Combustion Engines.” *Ph.D. at Ghent University* (2018)]

NO MODELLING

- Calculate heat flux from definition with temperature gradient

$$q_w = (\lambda_w + \lambda_{w,t}) \frac{d\bar{T}}{dy}|_w$$

- Low Reynolds formulation

  Resolve near wall behavior and temperature gradient
- High Reynolds formulation

  Tune by adjusting Pr_t

IMPLEMENTATION IN OPENFOAM

$$q_w = c_p(\alpha_w + \alpha_{w,t})\frac{d\bar{T}}{dy}|_w$$

α: Thermal diffusivity expressed in kg/m/s

Wall heat flux model $q_w = \frac{\rho c_p u_\tau T\, ln(T_w/T) - \frac{dP}{dt}\frac{\nu}{u_\tau}\left(\frac{y^+ - 40}{0.4767 + \frac{1}{Pr}} + 117.31\right)}{\frac{1}{0.4767}\left[ln(y^+ + \frac{1}{0.4767Pr}) - ln(40 + \frac{1}{0.4767Pr})\right] + 10.2384}$	$\alpha_{w,t} = \frac{q_w}{{d\bar{T}}/{dy}_w\, c_p} - \alpha_w$
Convective heat flux model $q_w = h\left(T_{gas} - T_w\right)$ $\frac{hL}{k} = Nu = a\, Re^b\, Pr^c$	$\alpha_{w,t} = \frac{q_w}{{d\bar{T}}/{dy}_w\, c_p} - \alpha_w$
No modelling $q_w = (\lambda_w + \lambda_{w,t})\frac{d\bar{T}}{dy}|_w$	$\alpha_{w,t} = 0 \quad or \quad \alpha_{w,t} = \frac{\mu_t}{Pr_t}$

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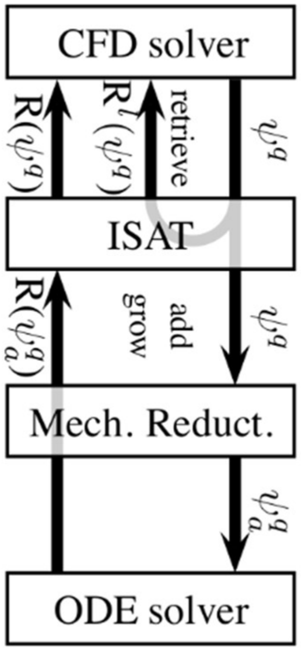
CHEMISTRY SOLVERS

TDAC

- Tabulated Dynamic Adaptive Chemistry
- Tabulate earlier chemistry solutions and try to retrieve “nearby” solutions
- Only keep active, important species before solving ODE

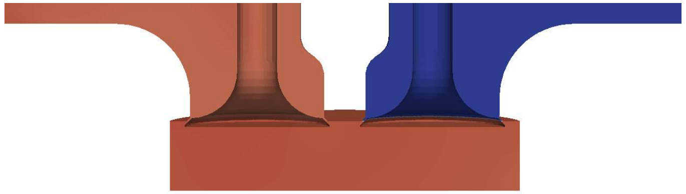


TDAC CCM

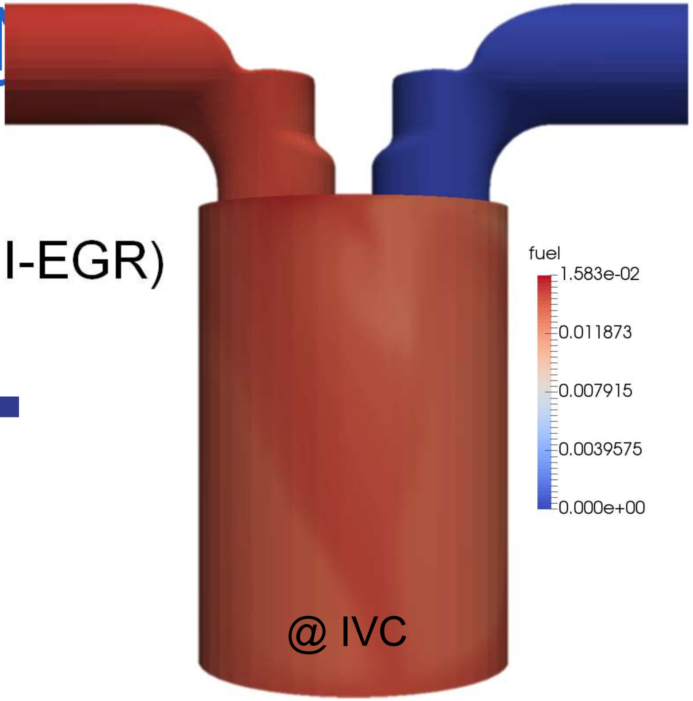
- Multi-zone chemistry
- Chemistry Coordinate Mapping
- Don’t tabulate, do reduction
- Instead group cells with almost equal state (p, ρ, T) and solve chemistry once for those cells.

MASS FRACTIONS-INITIALISATIO

- Do a full cycle gas dynamics simulation
  - Define mass fraction of important species at IVC (also I-EGR)
  - Check amount of fuel coming in (related with p, T)
  - Check stratification



@ -25° BTDC

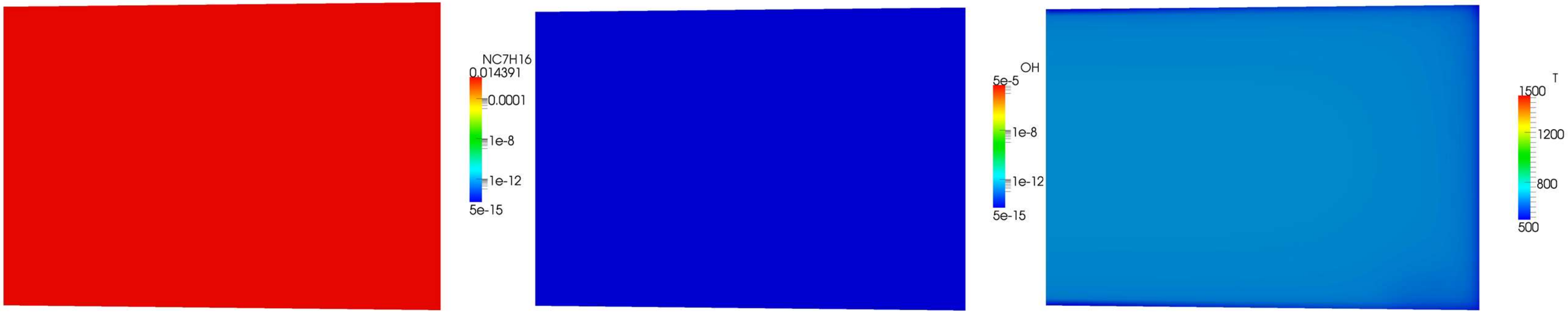


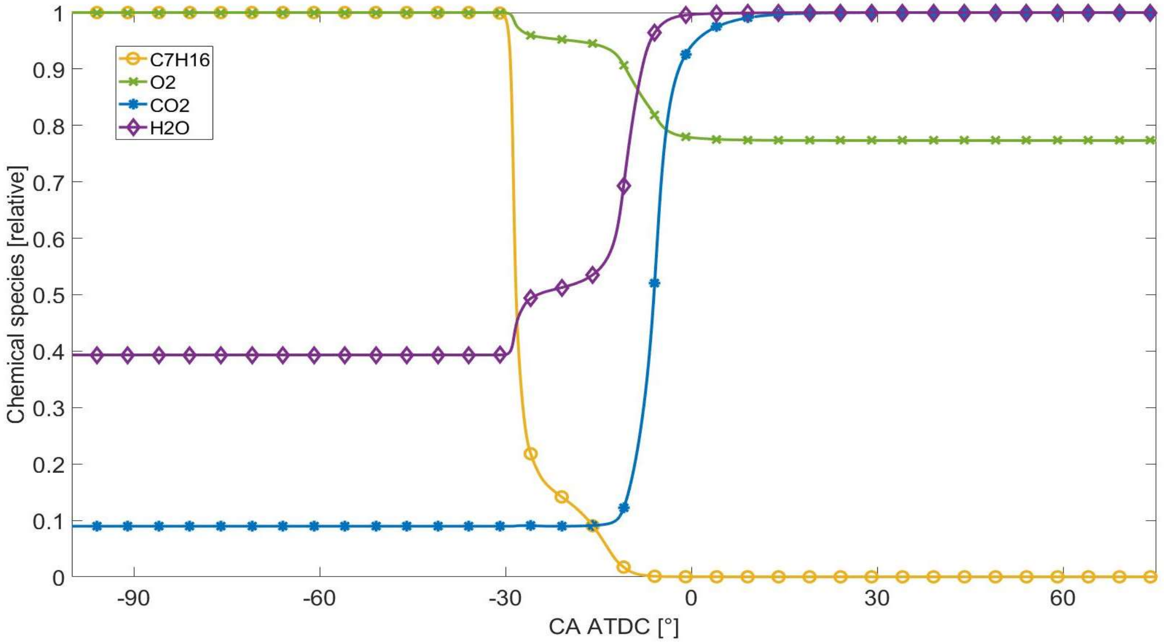
@ IVC

- Volumetric integral

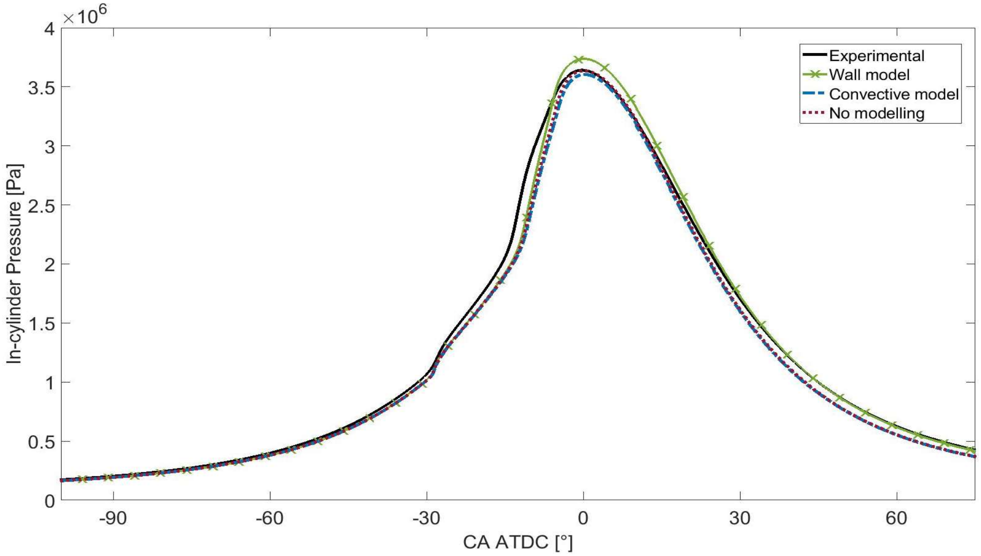
Species	**Mass fraction [%]**
Fuel = C_7H_{16}	1.439
O_2	22.102
N_2	74.694
H_2O	1.339
CO_2	0.426

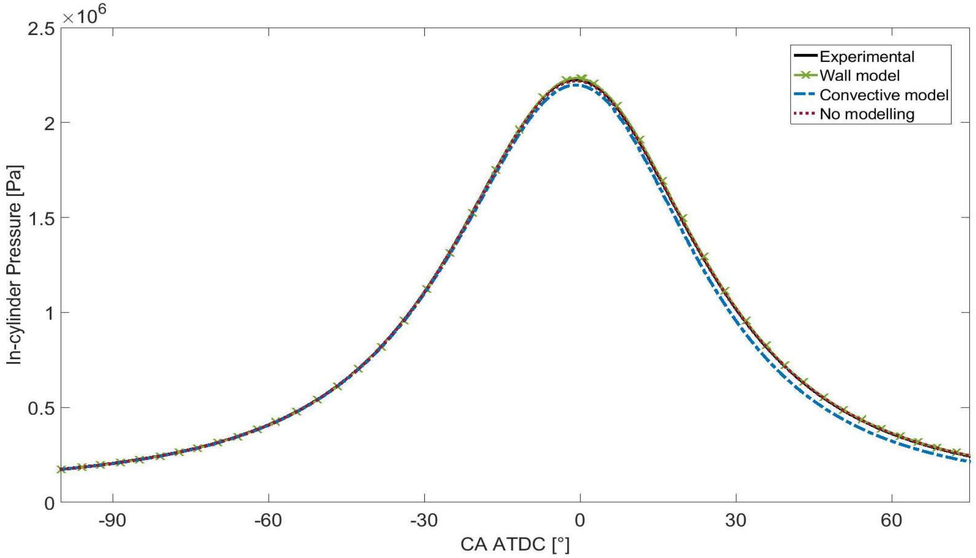
RESULTS

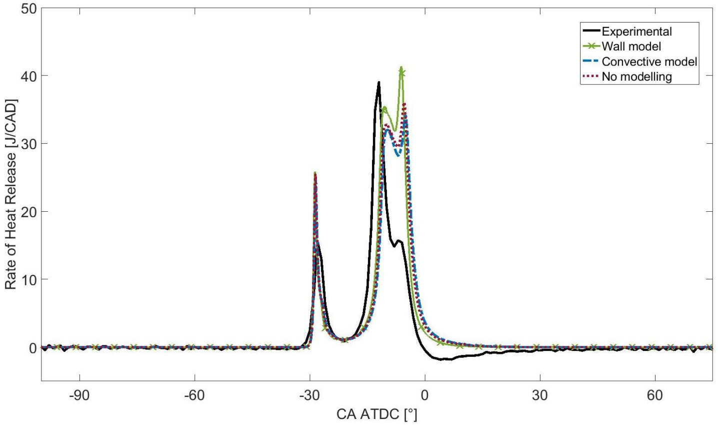

NC7H16
0.014391
0.0001
1e-8
1e-12
5e-15
OH
5e-5
1e-8
1e-12
5e-15
T
1500
1200
800
500

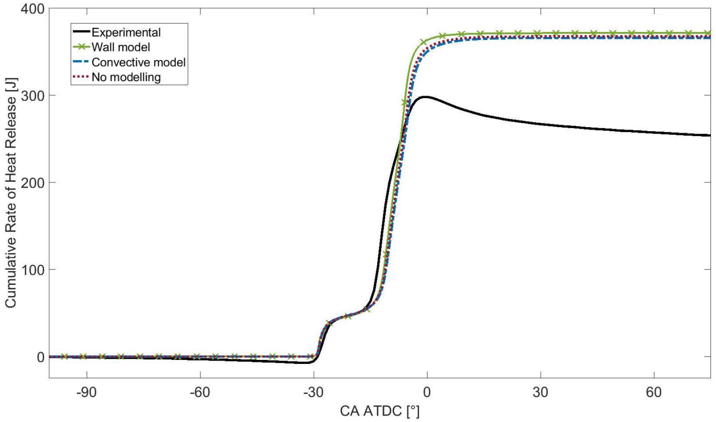

C7H16
O2
CO2
H2O
Chemical species [relative]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-90
-60
-30
0
30
60
CA ATDC [°]

RESULTS

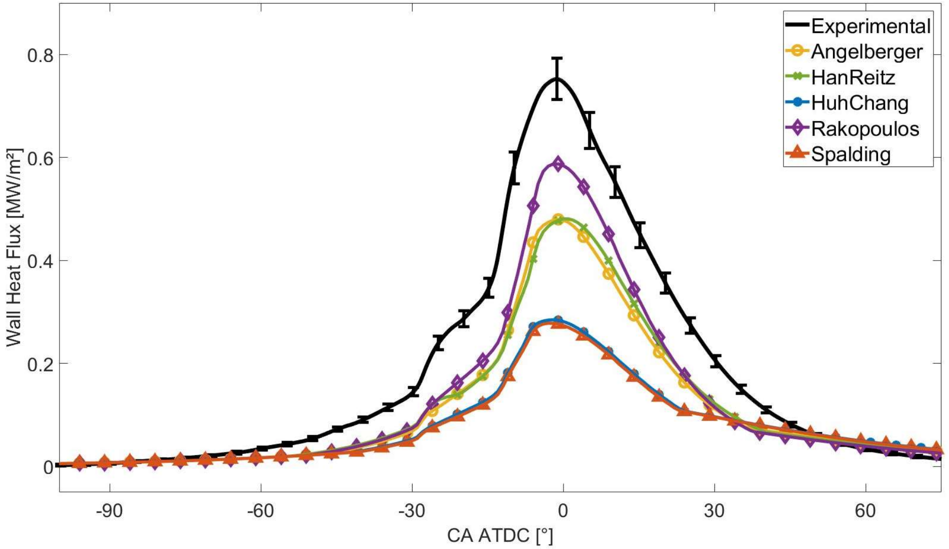

×10^6
4
3.5
3
2.5
2
1.5
1
0.5
0
In-cylinder Pressure [Pa]
-90
-60
-30
0
30
60
CA ATDC [°]
Experimental
Wall model
Convective model
No modelling

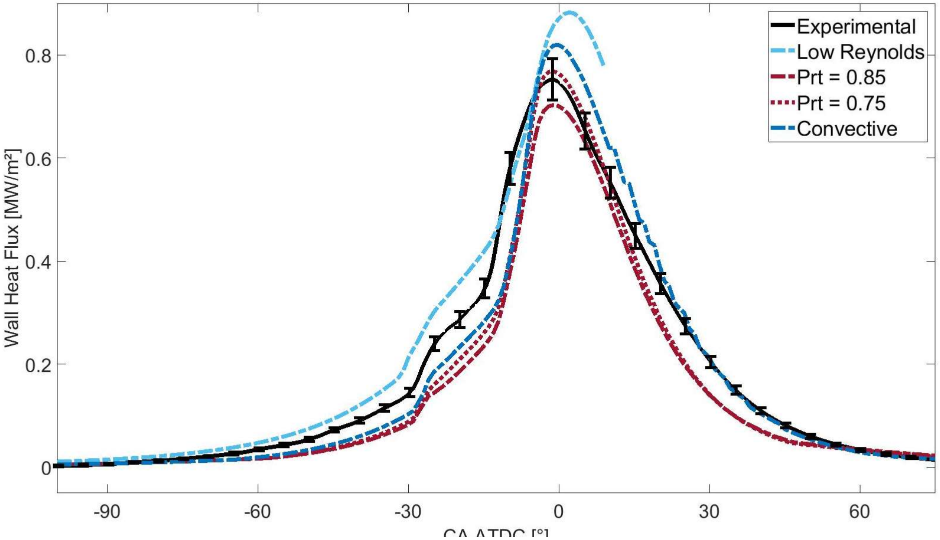

×10^6
2.5
2
1.5
1
0.5
0
In-cylinder Pressure [Pa]
-90
-60
-30
0
30
60
CA ATDC [°]
Experimental
Wall model
Convective model
No modelling

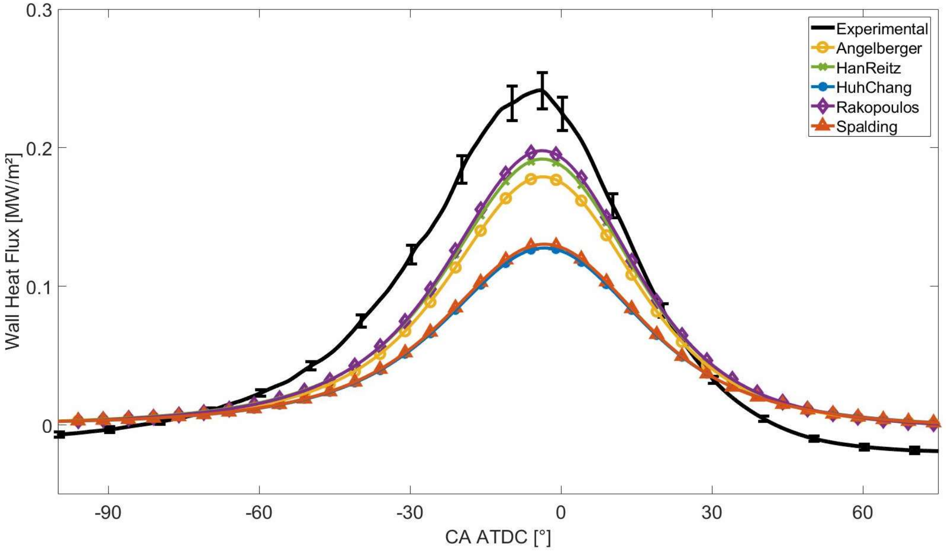

50
40
30
20
10
0
Rate of Heat Release [J/CAD]
-90
-60
-30
0
30
60
CA ATDC [°]
Experimental
Wall model
Convective model
No modelling

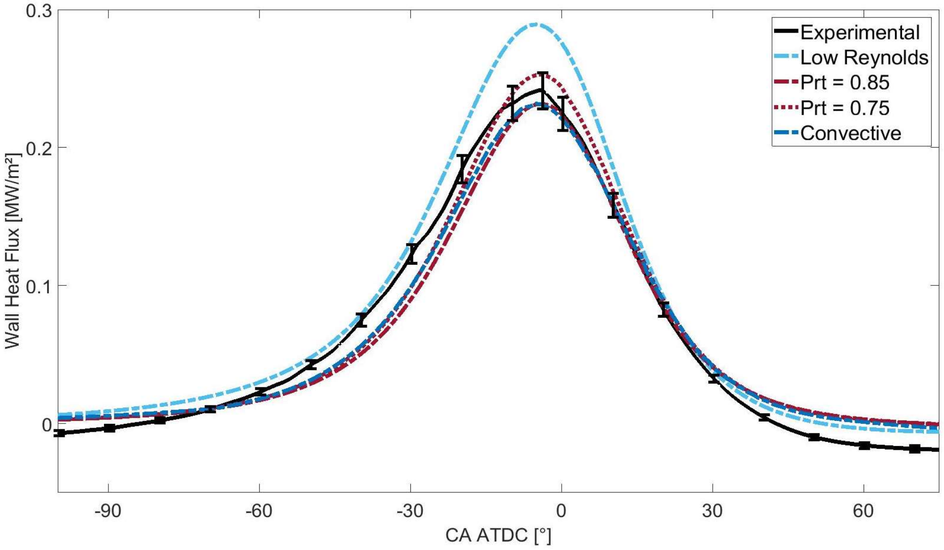

400
300
200
100
0
Cumulative Rate of Heat Release [J]
-90
-60
-30
0
30
60
CA ATDC [°]
Experimental
Wall model
Convective model
No modelling

RESULTS – QUALITATIVE

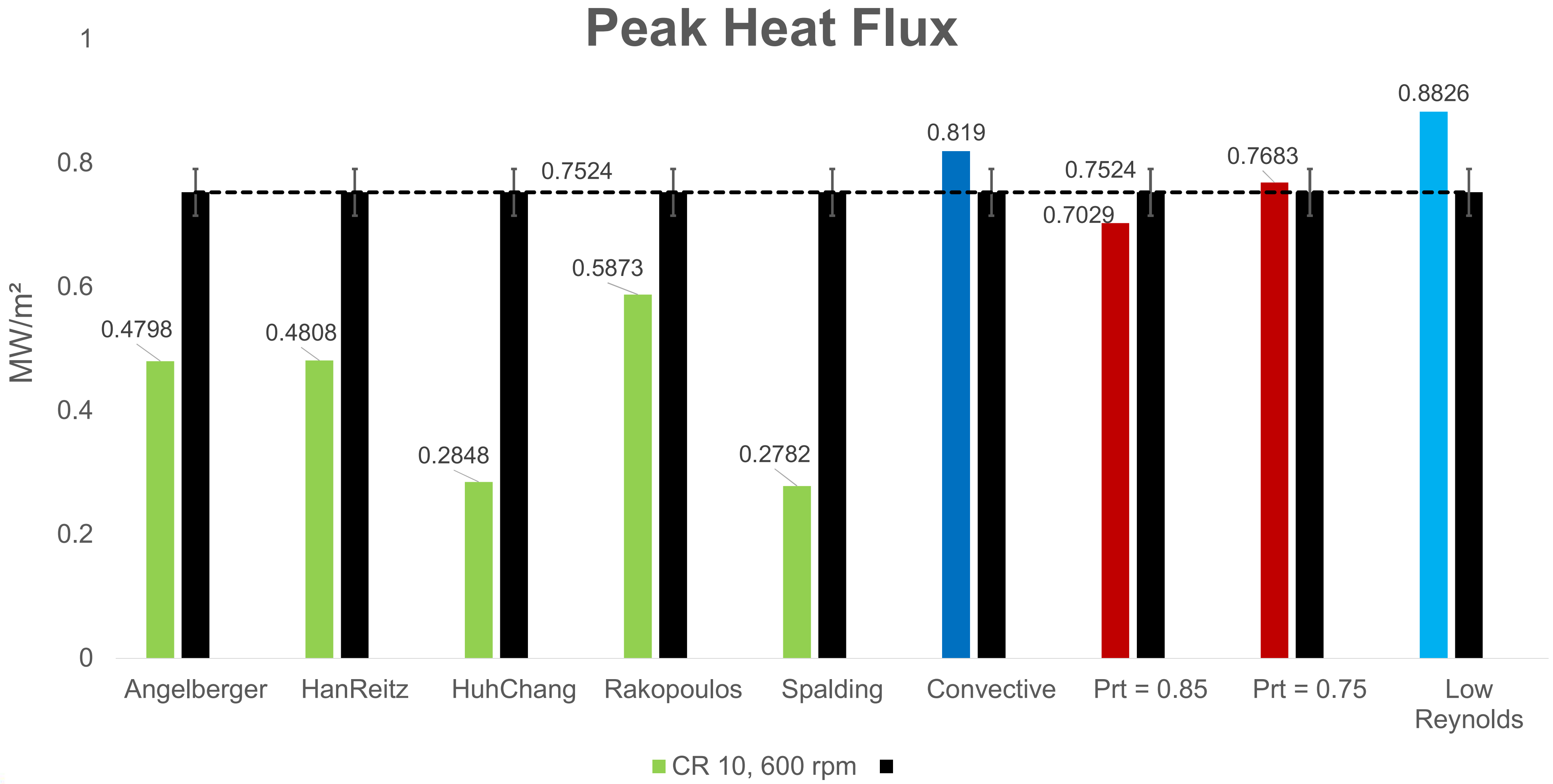








RESULTS – QUANTITATIVE



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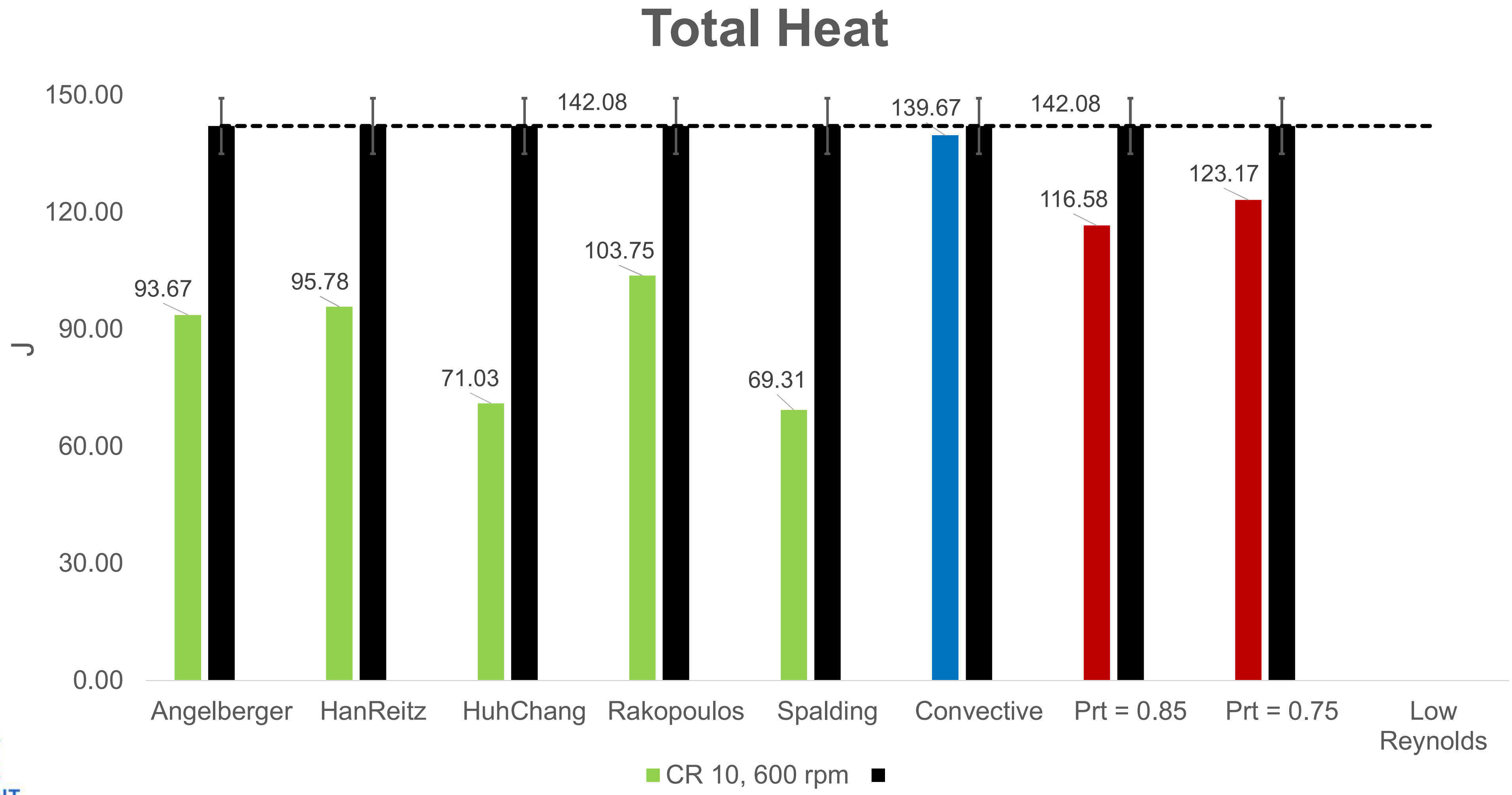
RESULTS – QUANTITATIVE



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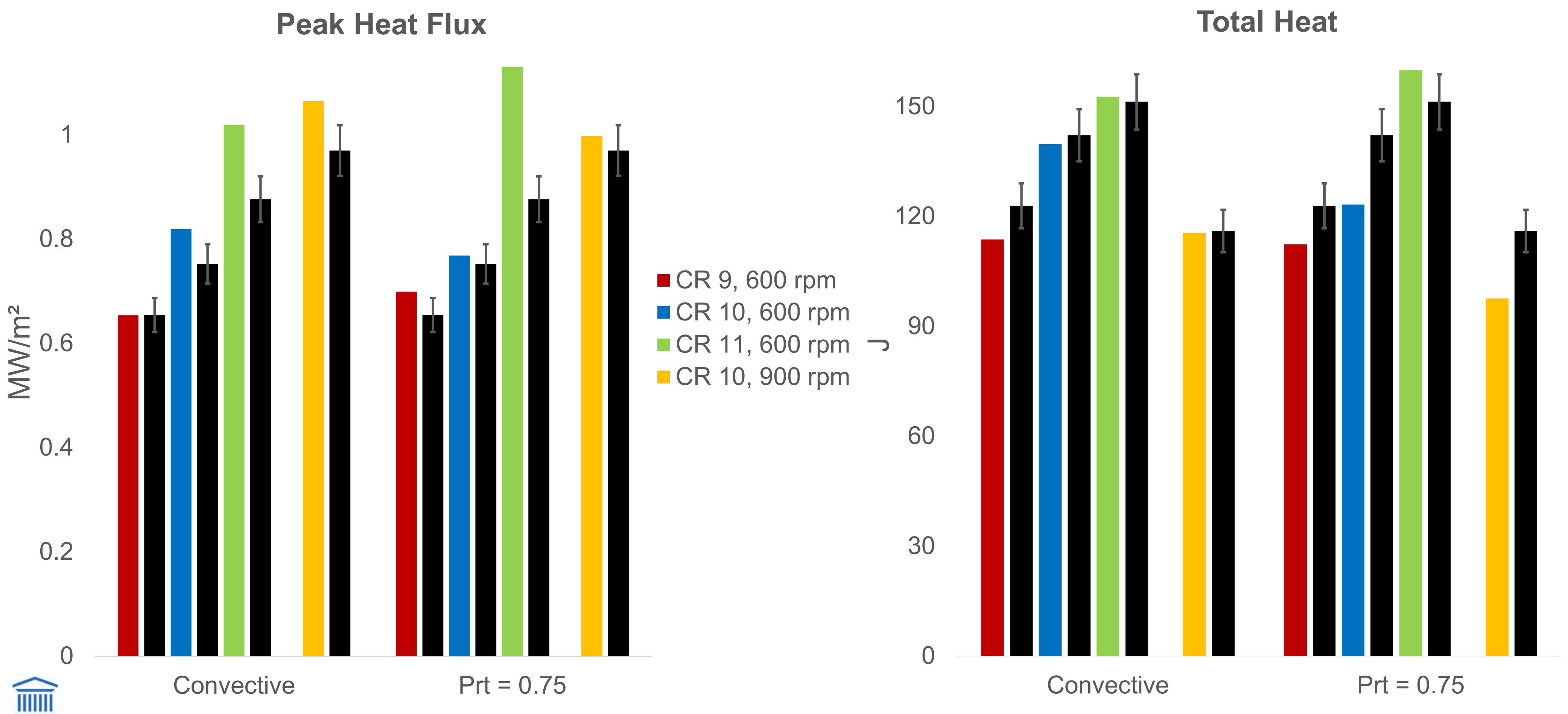
RESULTS – QUANTITATIVE



CONCLUSIONS

- Able to simulate HCCI operation and study the heat flux through ICE walls

- Wall heat flux models are not able to correctly capture heat flux in ICE’s,
    - Quantitatively and qualitatively
- Tuning with Pr_t allows a better prediction of the peak
    - Extension to other operations with same optimal constants doubtful
- Good results with convective law
    - Parameters look to be engine specific
- Low Reynolds approach better matches curve qualitatively, with good results considering peak and integral heat flux
    - Numerically intensive, impractical for 3D engine simulations
- For practical engine optimization:
    - 3D simulation with wall modelling of choice
    - Specific heat flux optimization with closed cycle low Reynolds formulation

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