Large-Eddy Simulations with Conjugate Heat Transfer of a Reacting Flow in an Internal Combustion Engine

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Large-Eddy Simulation for Energy Conversion in electric and combustion Engines

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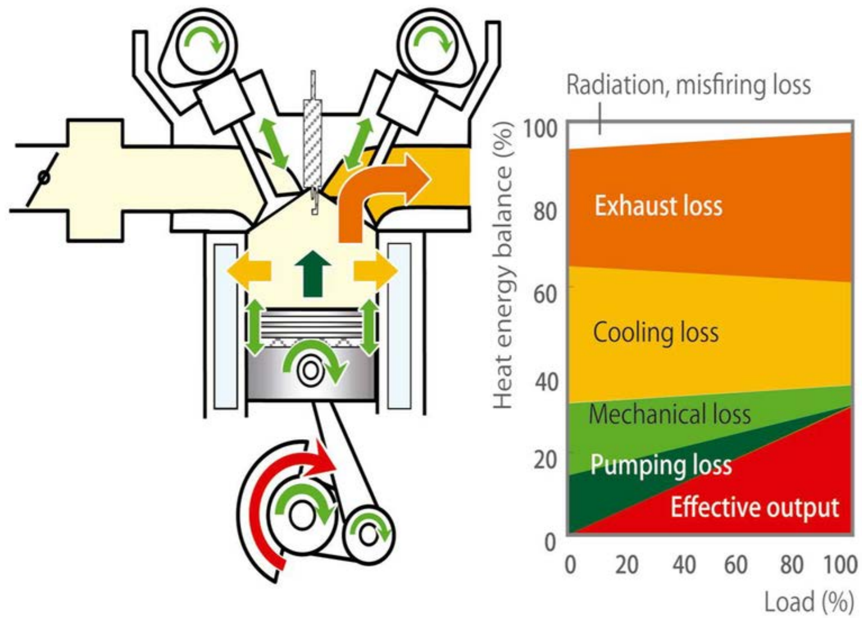
Motivation

- Engine heat transfer affects *efficiency, performance,* and *emissions.*

- Convective heat transfer controlled by the boundary layer development.

- Periodic changes in thermodynamic states throughout the cycle and large cycle-to-cycle variation (CCV) prevents a well-established boundary layer.

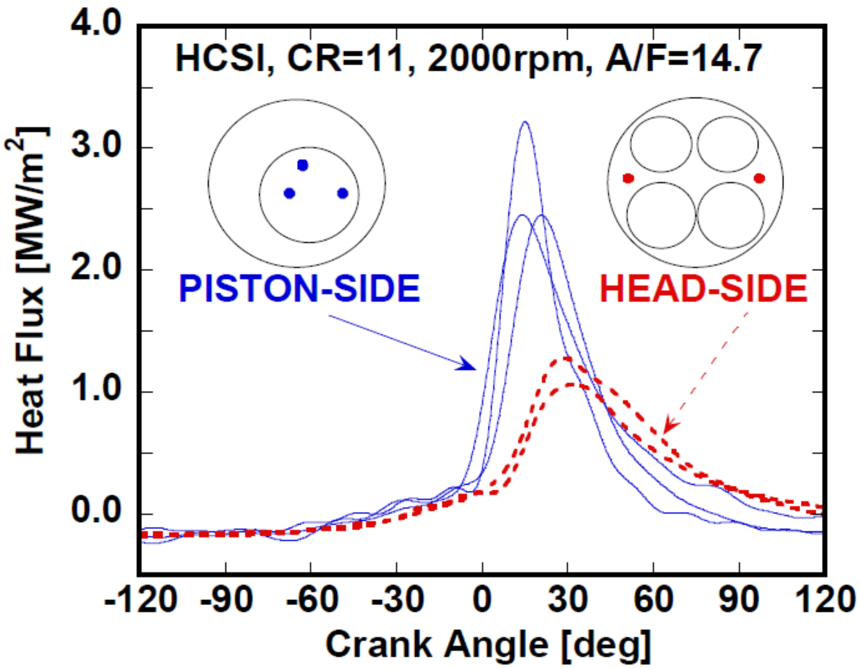
Typical energy split in ICEs [1].



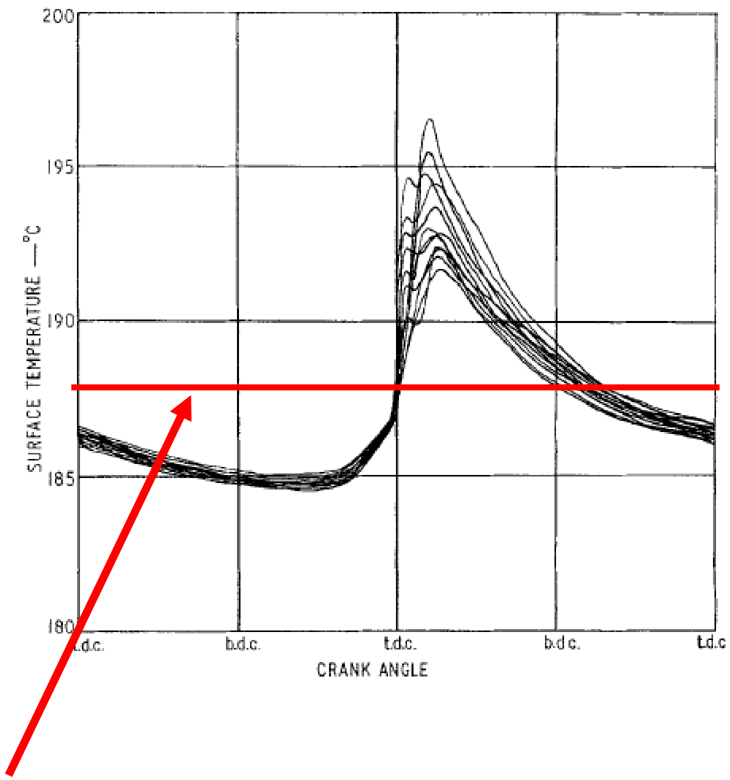
[1] greencarcongress.com

Heat Transfer Measurements

Engine heat transfer varies spatially and temporally [1].



Cycle-to-cycle variation in surface temperature [2].



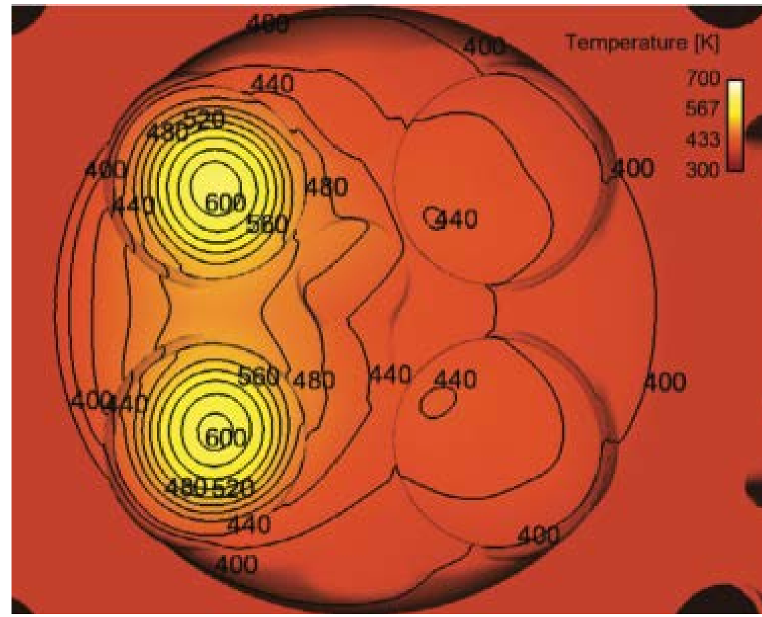
IC engine modeling typically uses steady, isothermal boundary conditions.

[1] Chang, J. et al. (2004), SAE-2004-01-2996,
[2] Annand, W.J.D., Ma, T.H. (1970), Proc. of the Ins. of Mech. Engineers.

Conjugate Heat Transfer (CHT)

- Spatially and temporally varying temperatures
- Heat transfer between fluid and solid
- Shortcomings:
  - Reynolds-Averaged Navier-Stokes (RANS) models
  - Fixed engine components
  - Validation needed
- Large-eddy simulations (LES) CHT performed by Misdariis *et al.*[1]:
  - Some cyclic and spatial variations
  - Shortcomings: fixed valves, valve motion on in-cylinder flow not simulated

Spatially varying temperature on the cylinder head [1].



Previous study [2]: Multi-cycle LES with CHT with moving solid components, validated with near-wall flow, temperature, and heat flux measurements.

This study: extend to fired operating condition.

[1] Misdariis, A., et al. (2015), Comb. and Flame.
[2] Wu, A., et al. (2019), OGST.

Objectives

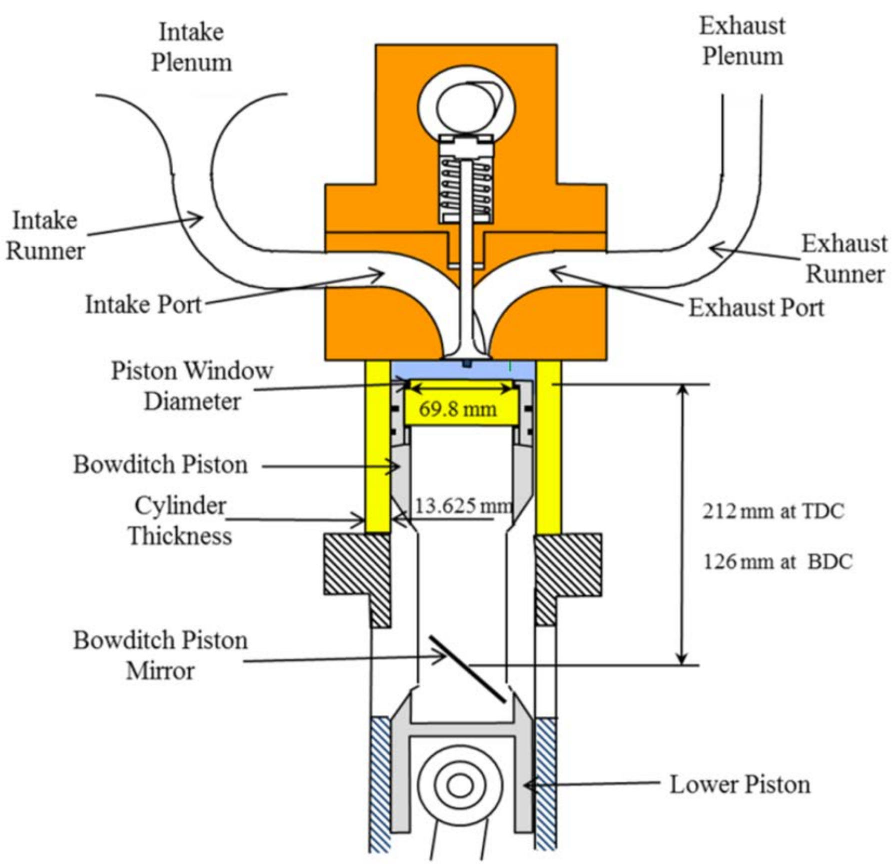
- Integrate CHT with LES for improved heat transfer predictions for fired engine operating condition to capture spatial, temporal, and cyclic variations in surface temperatures.

- Validate and assess CHT method in near-wall flow and temperature predictions with particle-image velocimetry (PIV) and planar laser-induced fluorescence (PLIF) data of the transparent combustion chamber (TCC-III) engine.

- Compare CHT to LES with uniform temperature boundary conditions.

TCC-III Engine

Extensive database on Deepblue

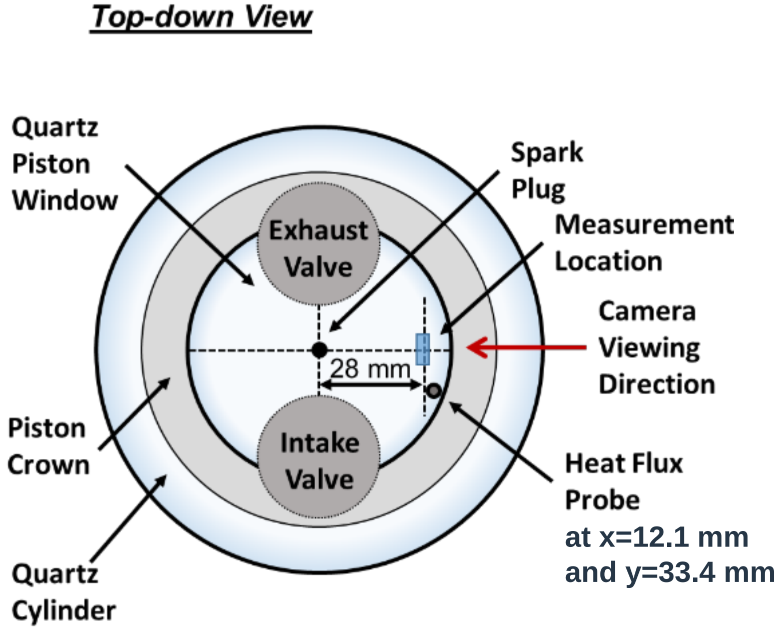


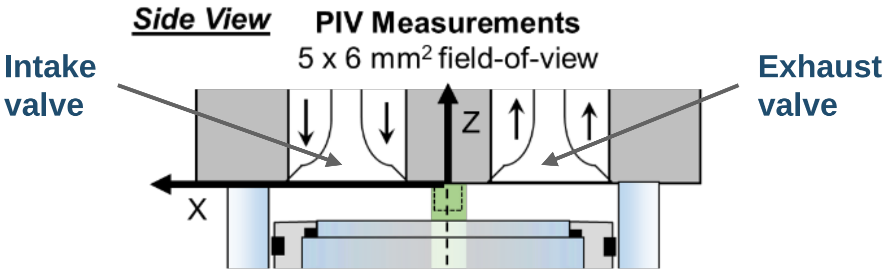
Parameter	Value
Engine operation	Fired (stoichiometric propane/air mixture)
Bore	92 mm
Stroke	86 mm
Clearance at TDC	9.5 mm
Compression ratio	10:1
Intake valve opening	352.8 CAD aTDCc
Intake valve closing	-119.2 CAD aTDCc
Exhaust valve opening	124.8 CAD aTDCc
Exhaust valve closing	-347.2 CAD aTDCc
Spark plug	AC Delco R44LTS

Near-Wall Velocity and Temperature Measurements

Engine conditions:

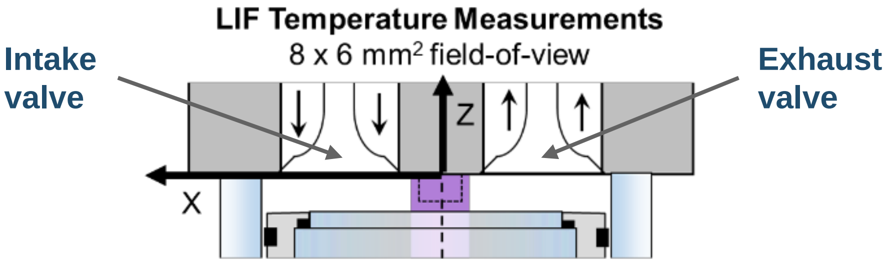
- 1300 RPM
- 40 kPa intake and 98 kPa exhaust manifold absolute pressure (MAP)
- 80 °C intake temperature





PIV dataset: [1]

- S_2016_03_25_09
- Resolution: 0.125 mm



PLIF dataset: [2]

- Resolution: 0.1 mm

Note: Uncertainty of ensemble average velocity less than 10% (P. C. Ma, *et al.* Intl. J. Engine Research (2017)).

[1] Greene, M. (2017). University of Michigan. PhD Thesis.
[2] Alzuabi, M. K. (2020). University of Michigan. PhD Thesis.

3D CFD Simulations with CONVERGE

LES model: Dynamic structure model
Number of cycles: 11 cycles, first cycle discarded

Wall models
- Werner and Wengle wall model
- Han and Reitz heat transfer model

Thermal boundary condition
- Uniform and constant surface temperature
- CHT, with supercycling

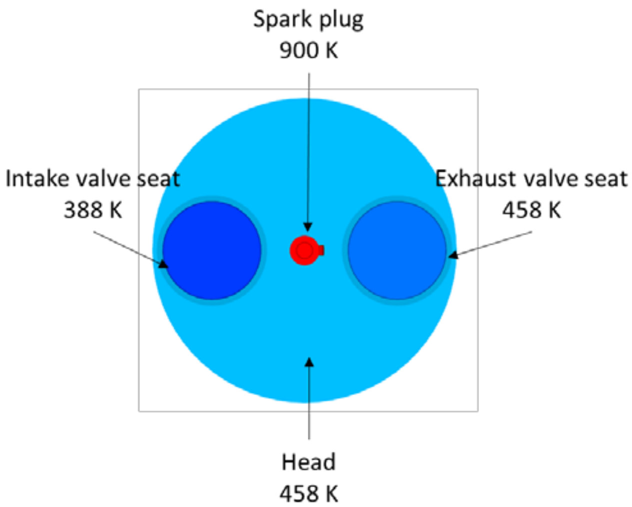
Combustion and Emissions Modeling
- G-equation model
- Laminar flame speed: Gülder correlation for propane
- Turbulent flame speed: Pitsch model, b_1 tuning
- Spark: energy source equal to 32 mJ at -18 CAD
- Extended Zel'dovich NOx model

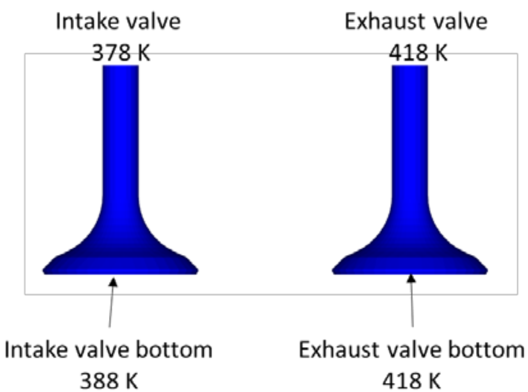
CONVERGE CFD SOFTWARE

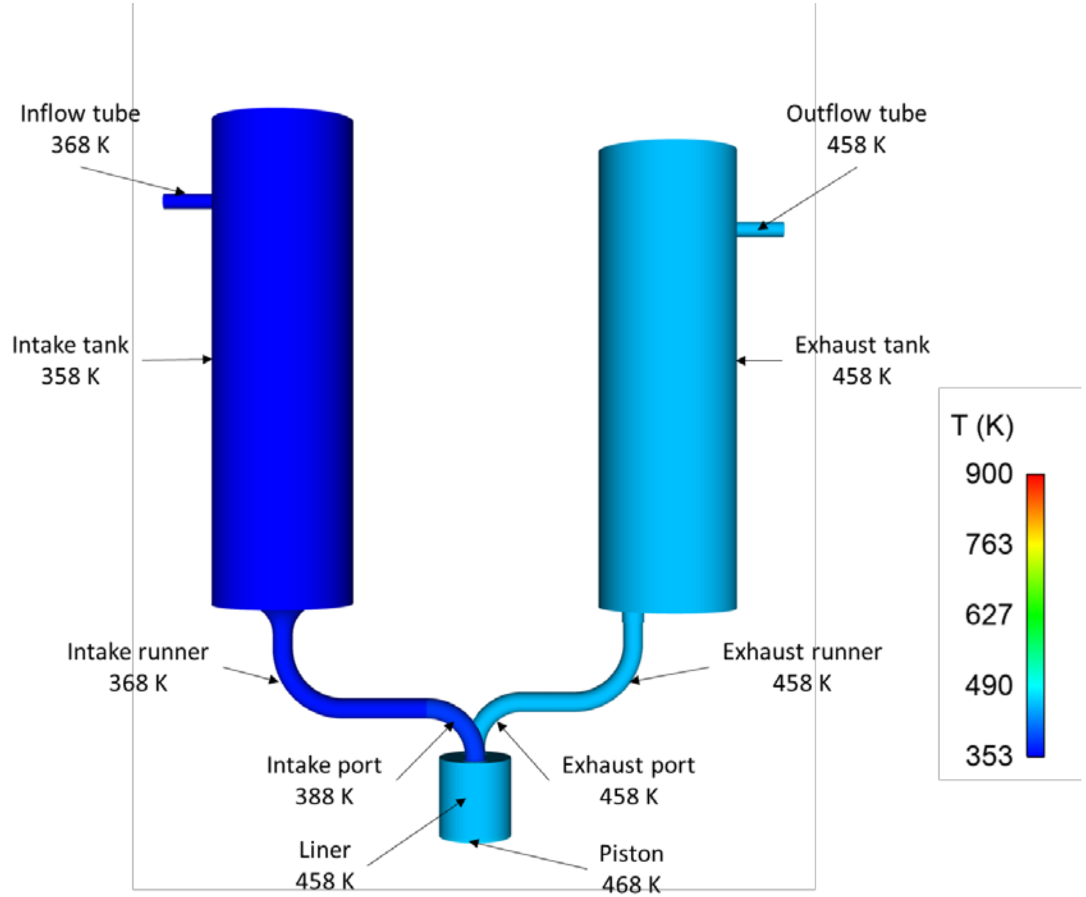
+

GT Gamma Technologies

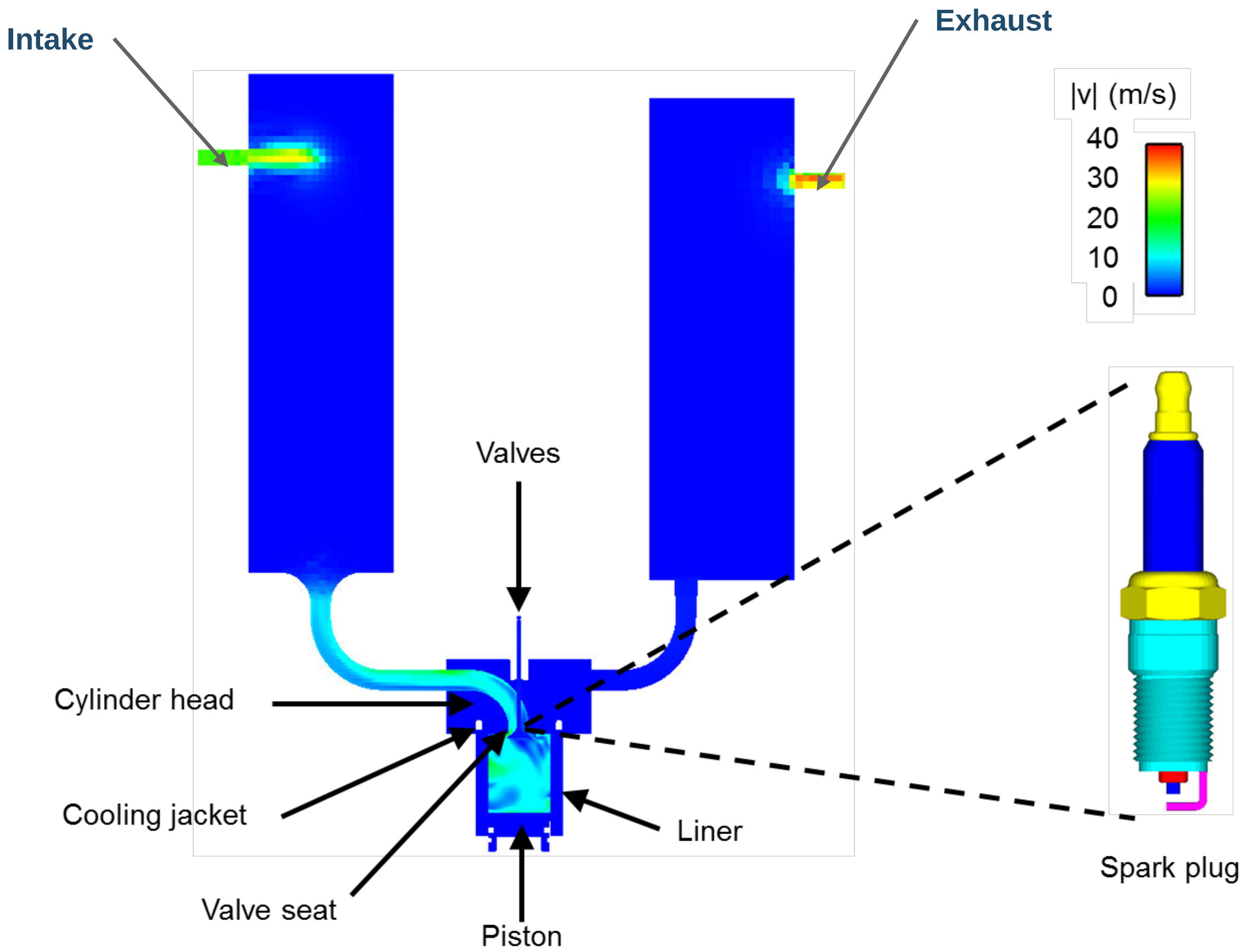
Thermal Boundary Conditions for the Fired Uniform Temperature Model



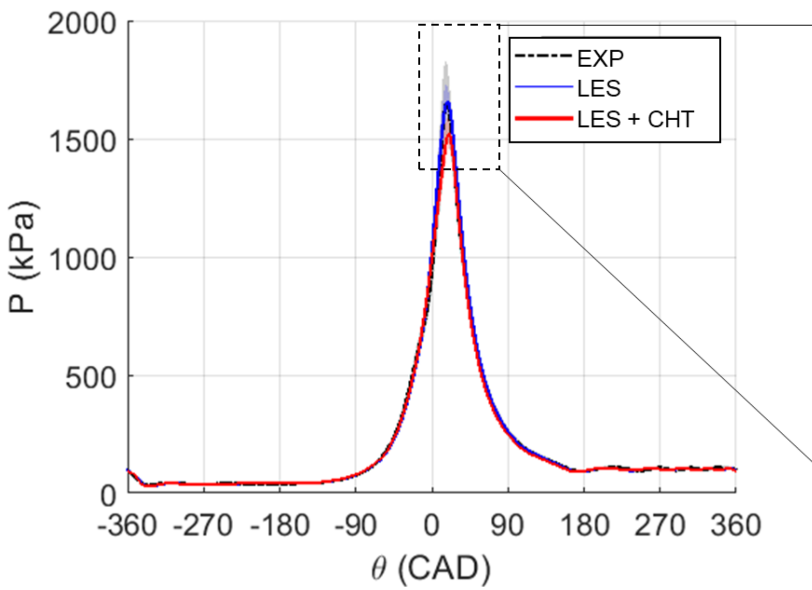


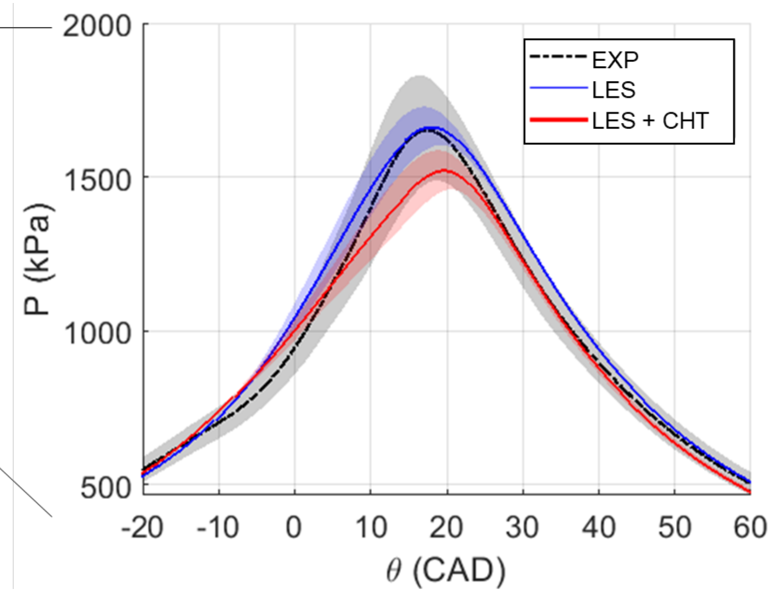


Computational Domain CHT model



LES Model Validation





- Note: b_1 tuning was required, which affects the turbulent flame speed (Pitsch model)

$$s_t = s_l\left(1 - \frac{b_3^2 s_l \mu_t}{2b_1 \mu u'} + \sqrt{\left(\frac{b_3^2 \mu_t s_l}{2b_1 \mu u'}\right)^2 + \frac{b_3^2 \mu_t}{\mu}}\right)$$

  – LES with uniform temperature BCs: b_1 = 5.5, CONVERGE 2.4
  – LES CHT: b_1 = 8, CONVERGE 3.0
- More tuning of b_1 is required for LES CHT, need to simulate all 10 cycles

Bulk temperature field and early flame kernel differences due to varying surface temperatures and differences in turbulent flame speed

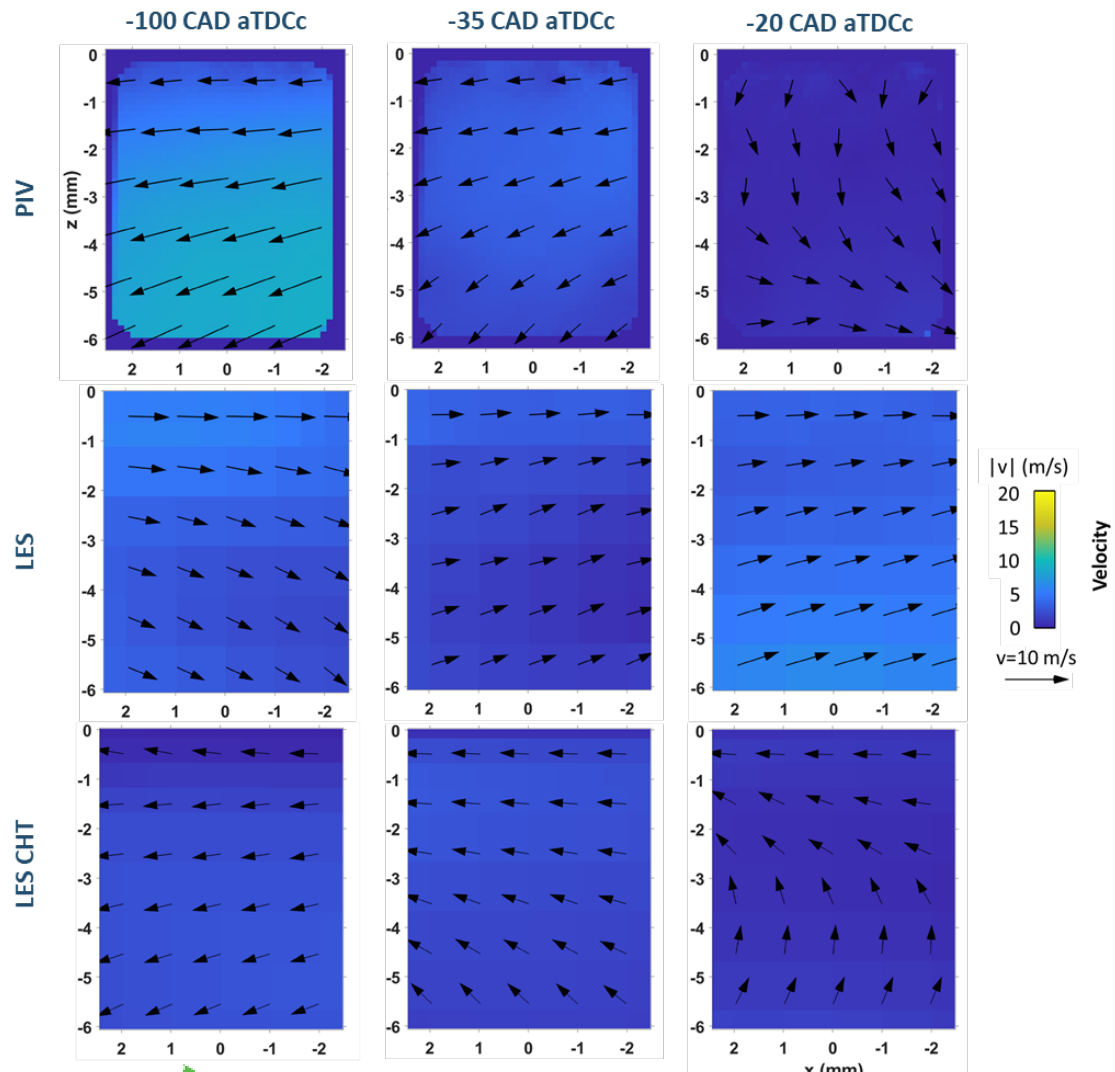
Uniform T LES

LES + CHT

- CHT has a larger b_1 value than uniform temperature LES, which affects turbulent flame speed
- Surface temperature also affects combustion process

Near-wall flow fields show improvements are still needed in wall modeling approach of engine LES

- CHT: accurate flow direction at -100 and -35 CAD, but opposite flow at -20 CAD, comparable velocity magnitude
- Uniform T LES: opposite flow with higher velocity magnitude at -100 and -35 CAD, and perpendicular and stronger flow at -20 CAD
- Flow field comparisons need to be done with caution
  - Abraham [1] found flow pattern switching in the TCC engine
  - Low number of simulated cycles

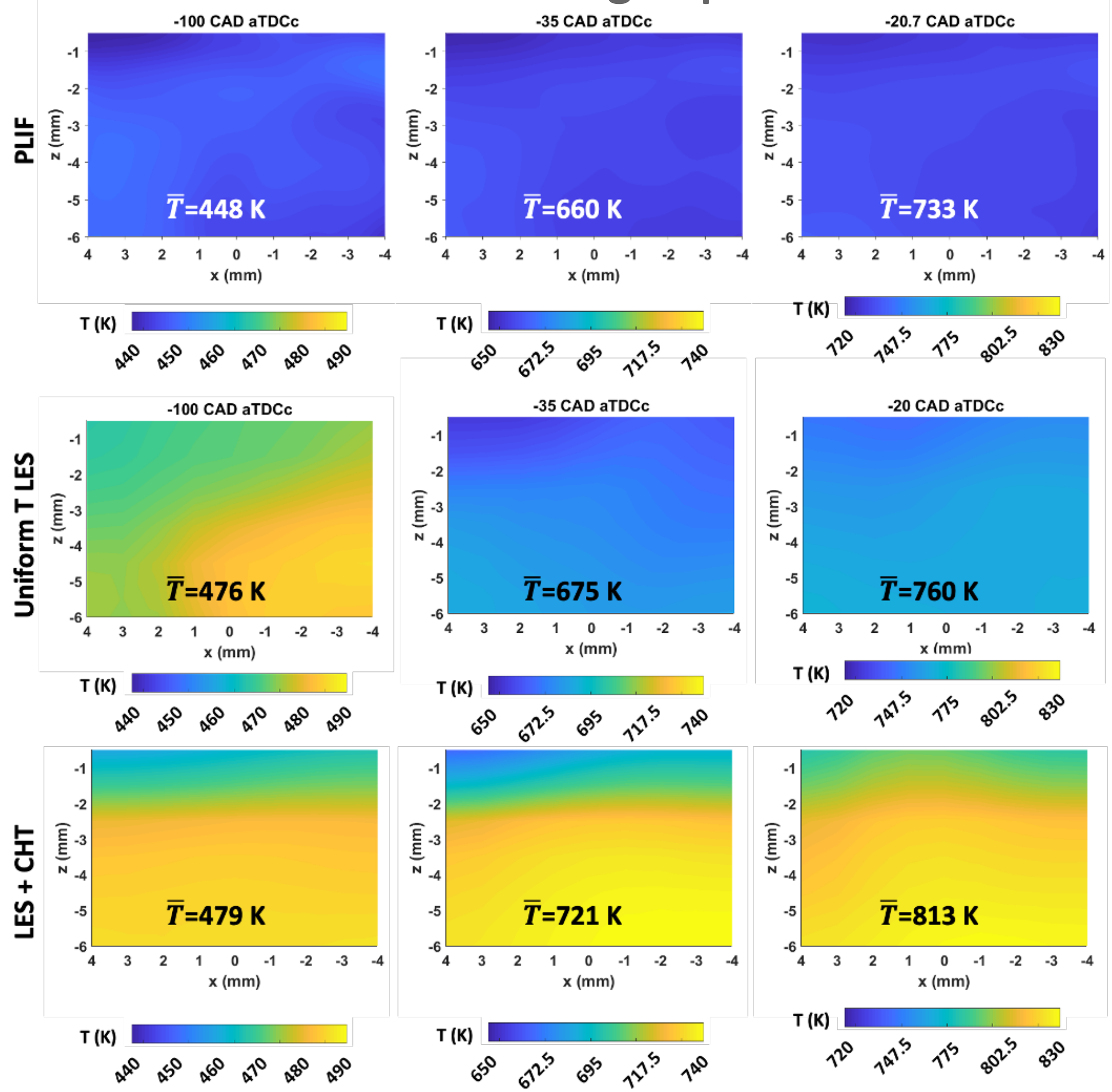


PIV: 184 cycles
LES: 10 cycles

[1] Abraham, P. et al, IJER, 2015.

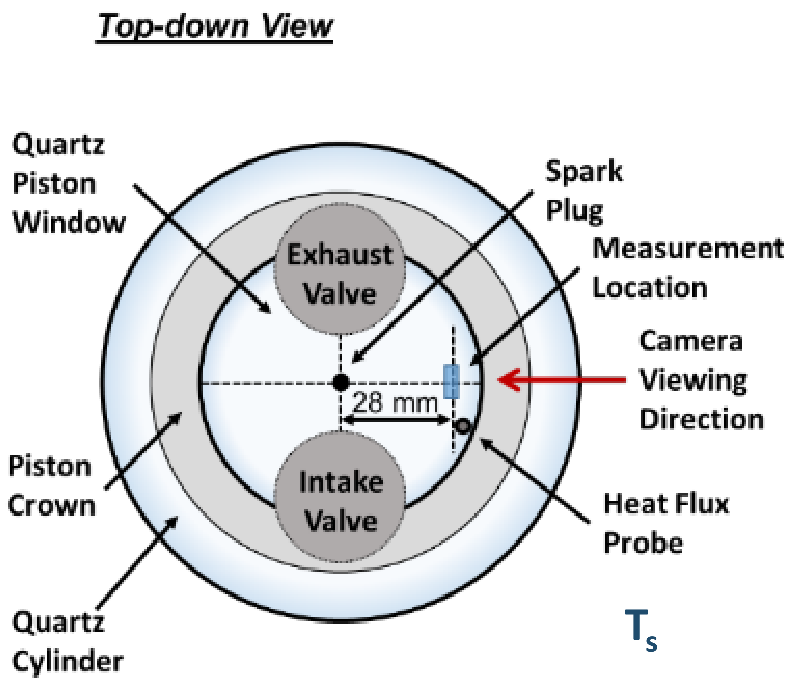
Near-wall temperature fields also need wall modeling improvements

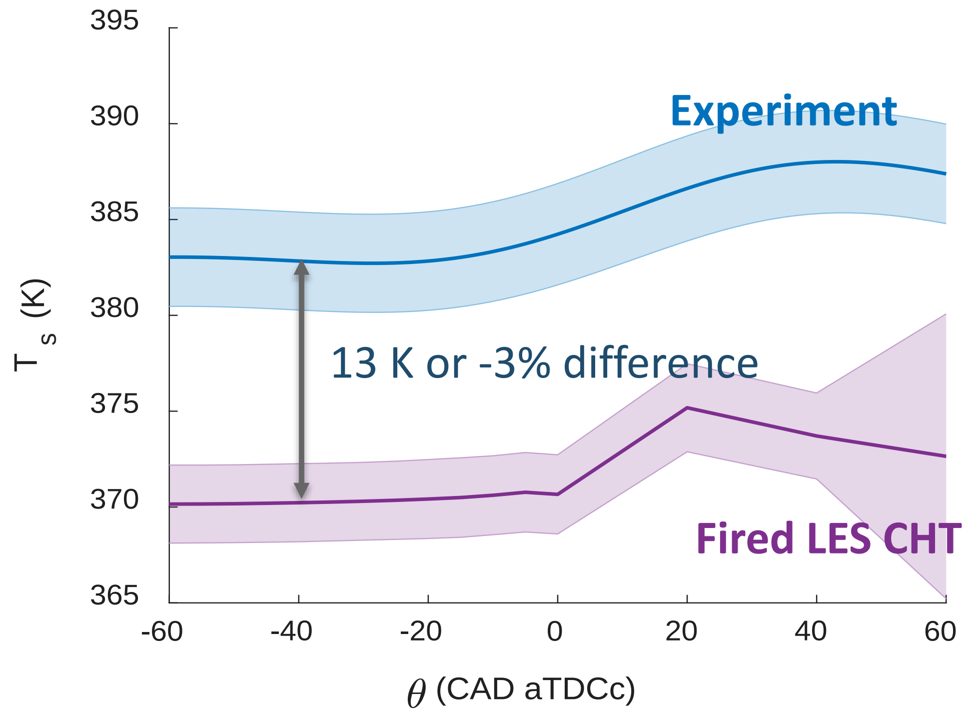
- Simulations predict higher temperatures than measured
- Measurements show smaller structures and the need for mesh refinement
- Simulated temperatures increase with wall distance
- Higher near-wall temperatures predicted by CHT than uniform T LES except at -100 CAD



PLIF: 145 cycles
LES: 10 cycles

CHT Surface Temperature Predictions



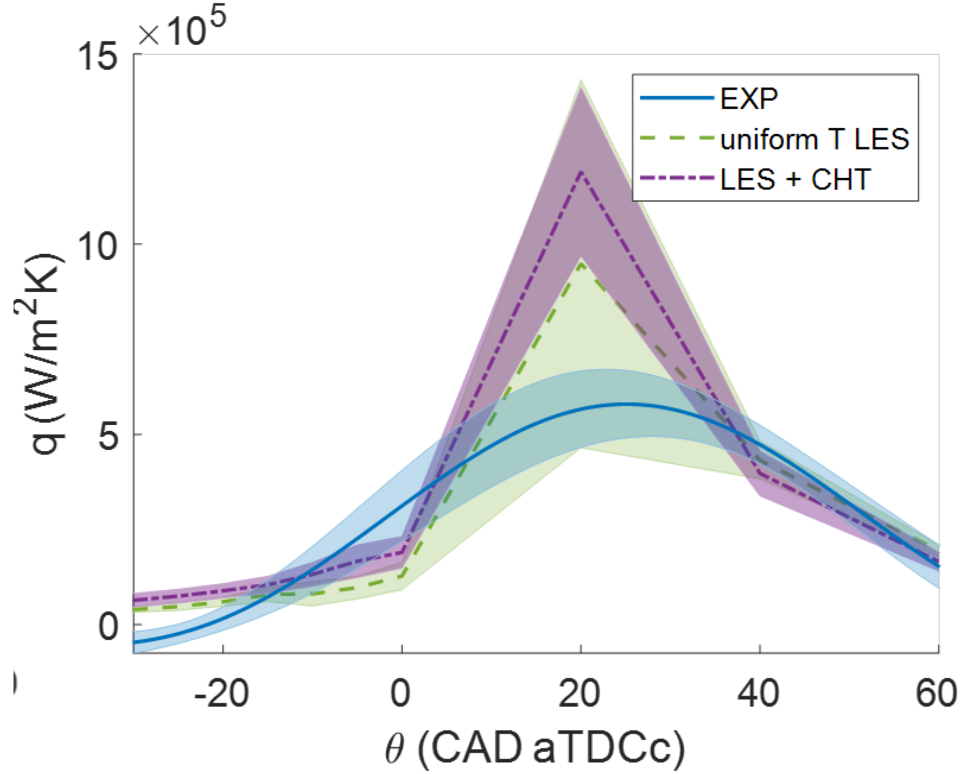


- Dynamics are captured
- Level of CCV after 40 CAD was overpredicted

Temporal and cyclic variations in surface heat flux

Note: experimental data filtered to reduce noise, but lowered peak heat flux from 990 kW/m²K to 579 kW/m²K

- CHT predicts largest peak heat flux of 1191 kW/m²K
- Uniform T model predicts peak heat flux of 949 kW/m²K
- CHT predicts a level of CCV closer to the measurement due to more consistent ΔT from cycle to cycle

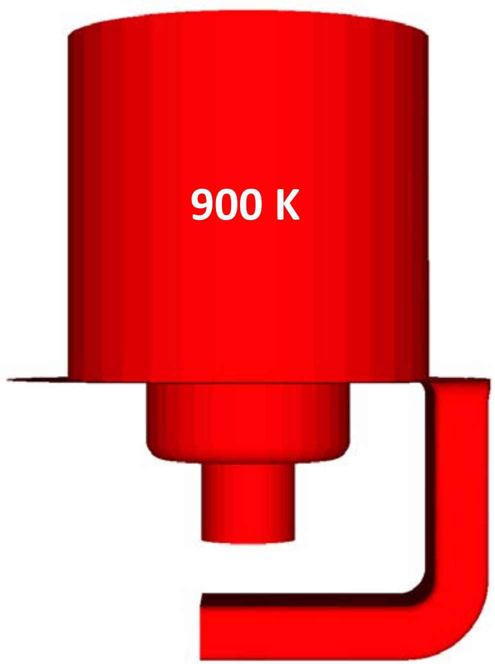


(b)

CHT model predicts spatial, temporal, and cyclic variation of surface temperature at the spark plug

Spatial variation

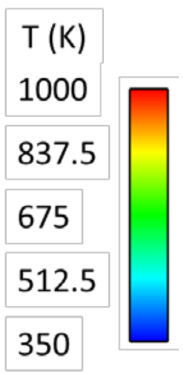
Uniform T LES



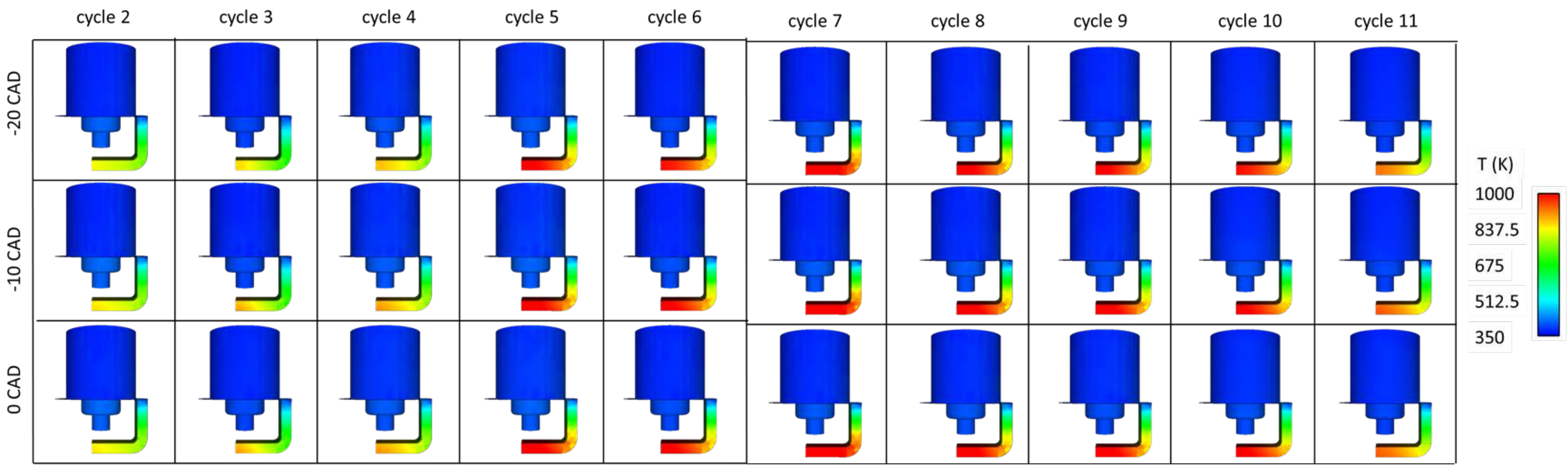
Cycle-to-cycle variation
Cycle 2-11

-20 CAD aTDCc

Temporal variation
Cycle 7



Spark plug temperature varies with time, space, and from cycle to cycle, and increases over cycles as engine warms up, even with supercycling.



	exp	CHT cycles 2-11	CHT cycles 5-11	Uniform T LES
IMEP ensemble avg	302 kPa	284 kPa	169 kPa	317 kPa
IMEP COV	0.85%	2%	0.86%	0.44%

Conclusions

- Near-wall predictions show improvements are needed in wall models, even with improved surface temperature boundary conditions from LES CHT. However, comparisons should be done with caution.
- CHT model predicted surface temperatures within 3% of measured cylinder head temperature.
- CHT model overpredicted peak heat flux but comparable level of CCV as the measurement.
- CHT model predicts large spatial, temporal, and cyclic variations in spark plug surface temperature ranging from 350 to 1000 K.
- Spark plug temperature increased gradually from cycle 2 to 4 even with supercycling.

Thank you for your attention

Questions?