Measurement and Computation of Fire Phenomena (*MaCFP*)

Case 3: Turbulent pool fires with liquid fuel – Waterloo Methanol Pool Flame

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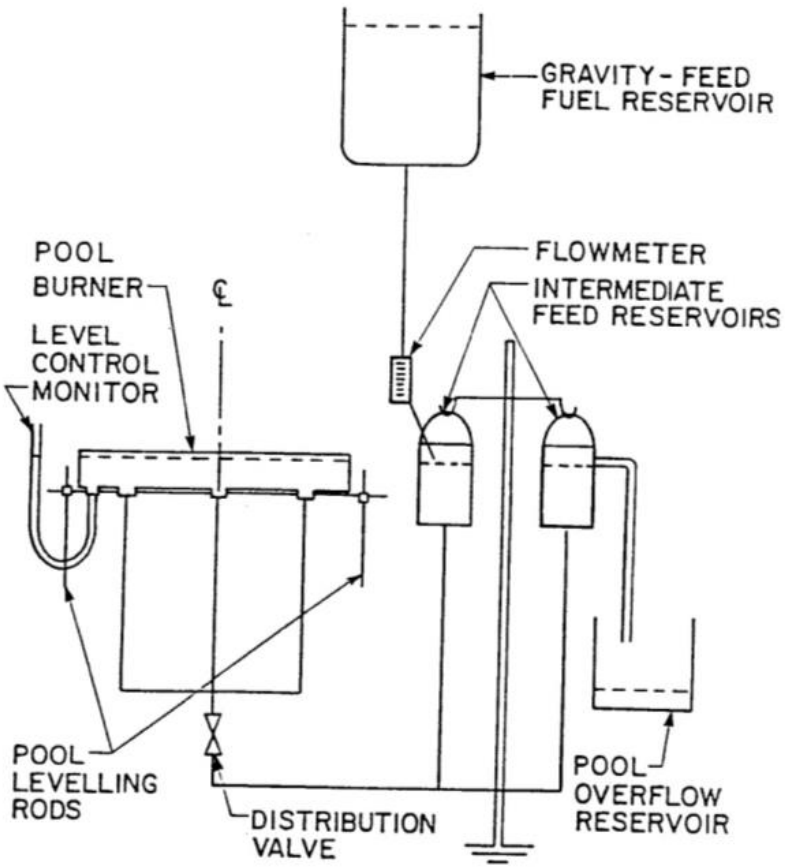
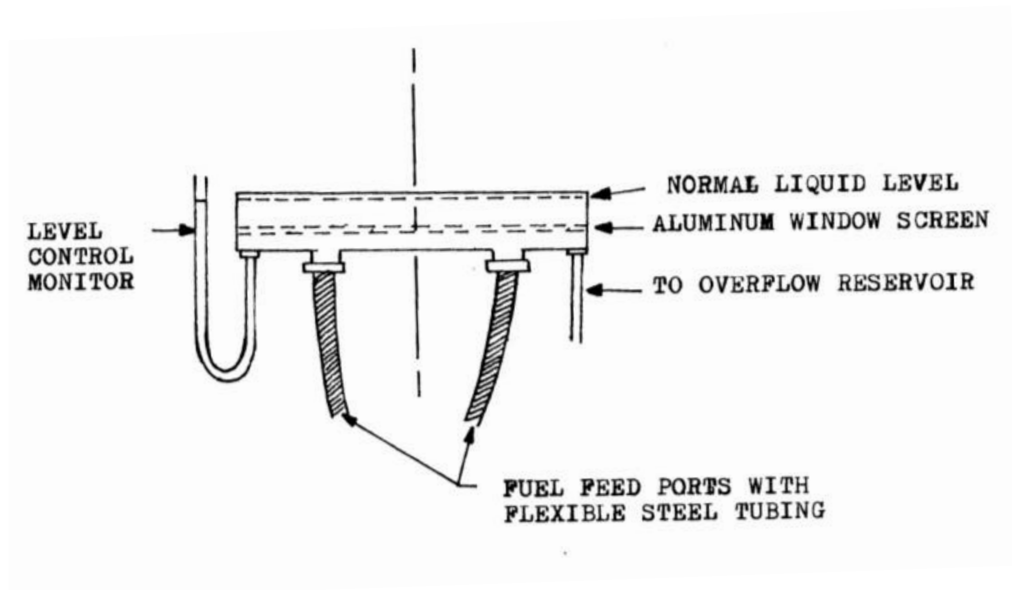
UNIVERSITY OF WATERLOO

UNIVERSITY OF MARYLAND

Methanol Pool Flame Experiment





Fuel feed rate 1.35 cm3/s

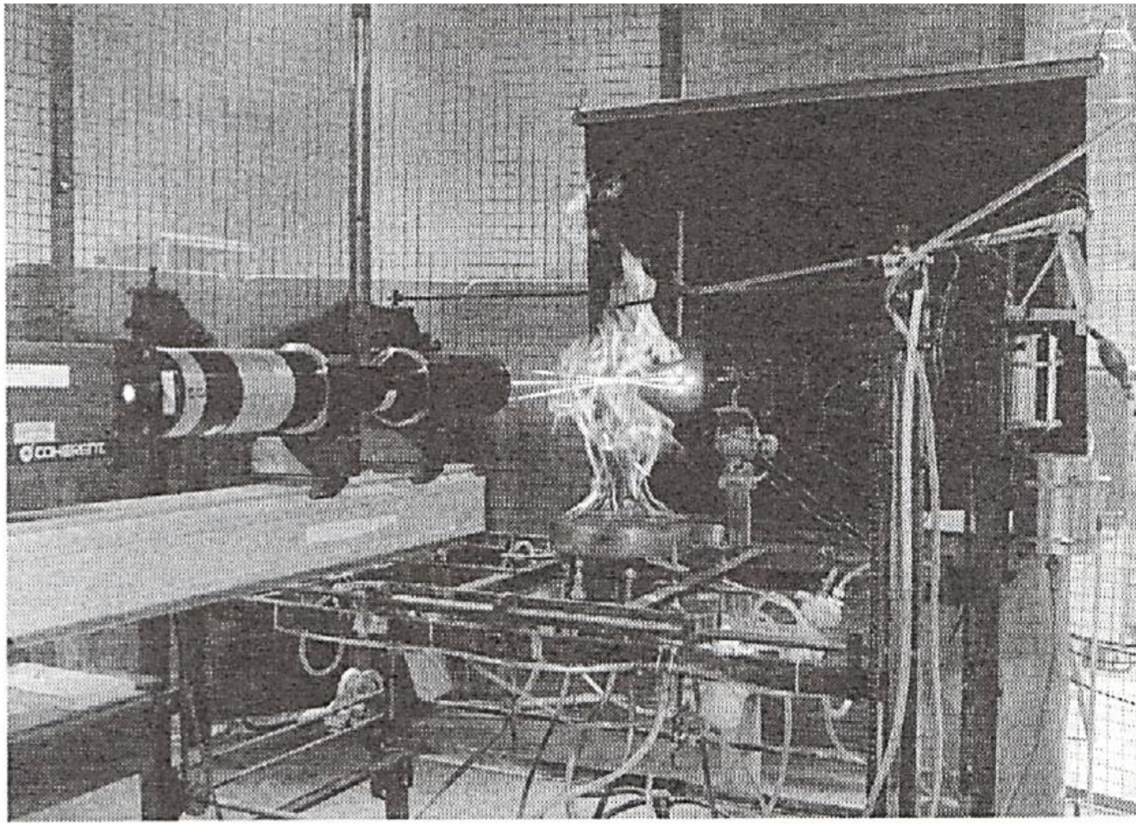
Modified overflow pan burner, 30.5 cm diameter

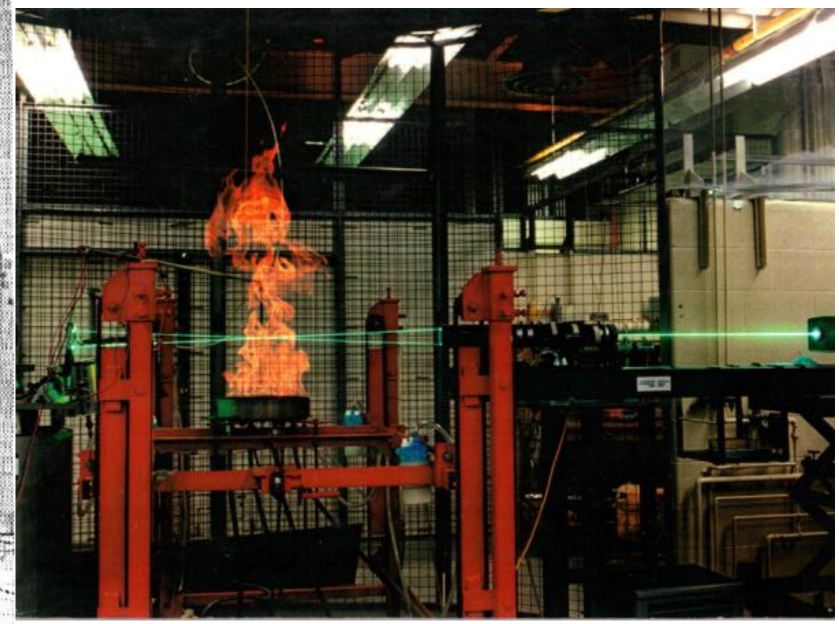
Fixed level (1 cm rim height), gravity fed methanol pool fire

Methanol Pool Flame Burner

- traversing stand allows radial and axial traverses of the fire flra
- burner moved while the velocity and temperature transducers held at a fixed point
- free ambient air entrainment into the fire from the base and sides
- natural draft fume hood
- fire sheilded from draughts by wire mesh covered with aluminum window screen.
- instrumentation operated from outside the enclosure

Methanol Pool Flame Experiment





Fine wire thermocouples, LDV point measurements

2-cm intervals, centerline to 16 cm radially

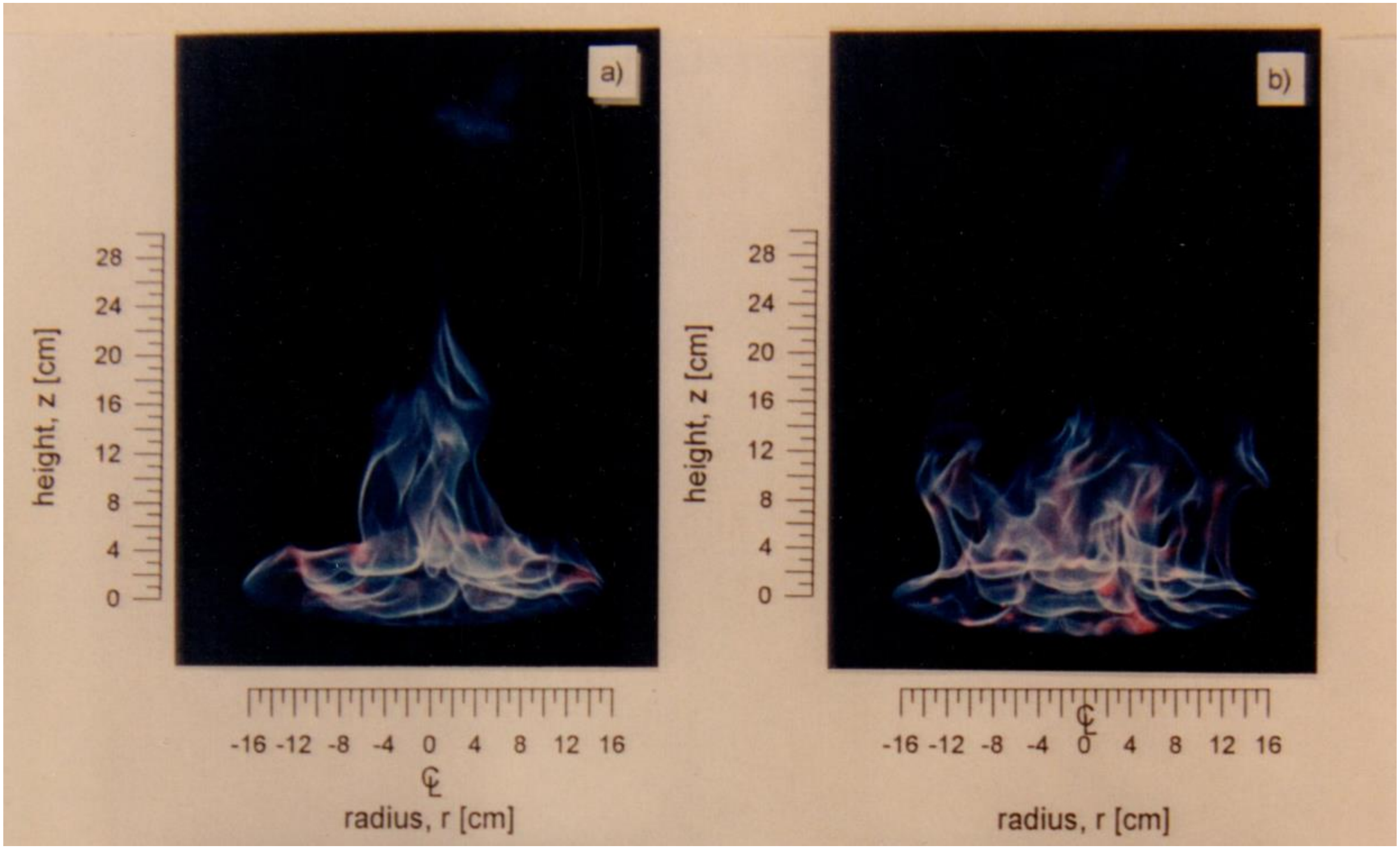
Heights from 2 to 20 cm and 30 cm above the fuel

Waterloo Methanol Pool Flame

Liquid fuel (methanol); steady state conditions

- Evaporation rate assumed constant and estimated from experimental measurements
- Constant liquid level in fuel pan (rim height = 1 cm)
- Small flame (D = 30.5 cm; HRR = 22.6 kW; $L_f \sim 0.5$ m)
- Laminar-to-turbulent transition at $z \sim 0.1$-0.2 m
- Methanol: non-sooting fuel ($\chi_{rad} \sim 17$-18%)
- Flame (puffing) instability: periodic shedding of large-scale structure ($f = 2.8$ Hz)

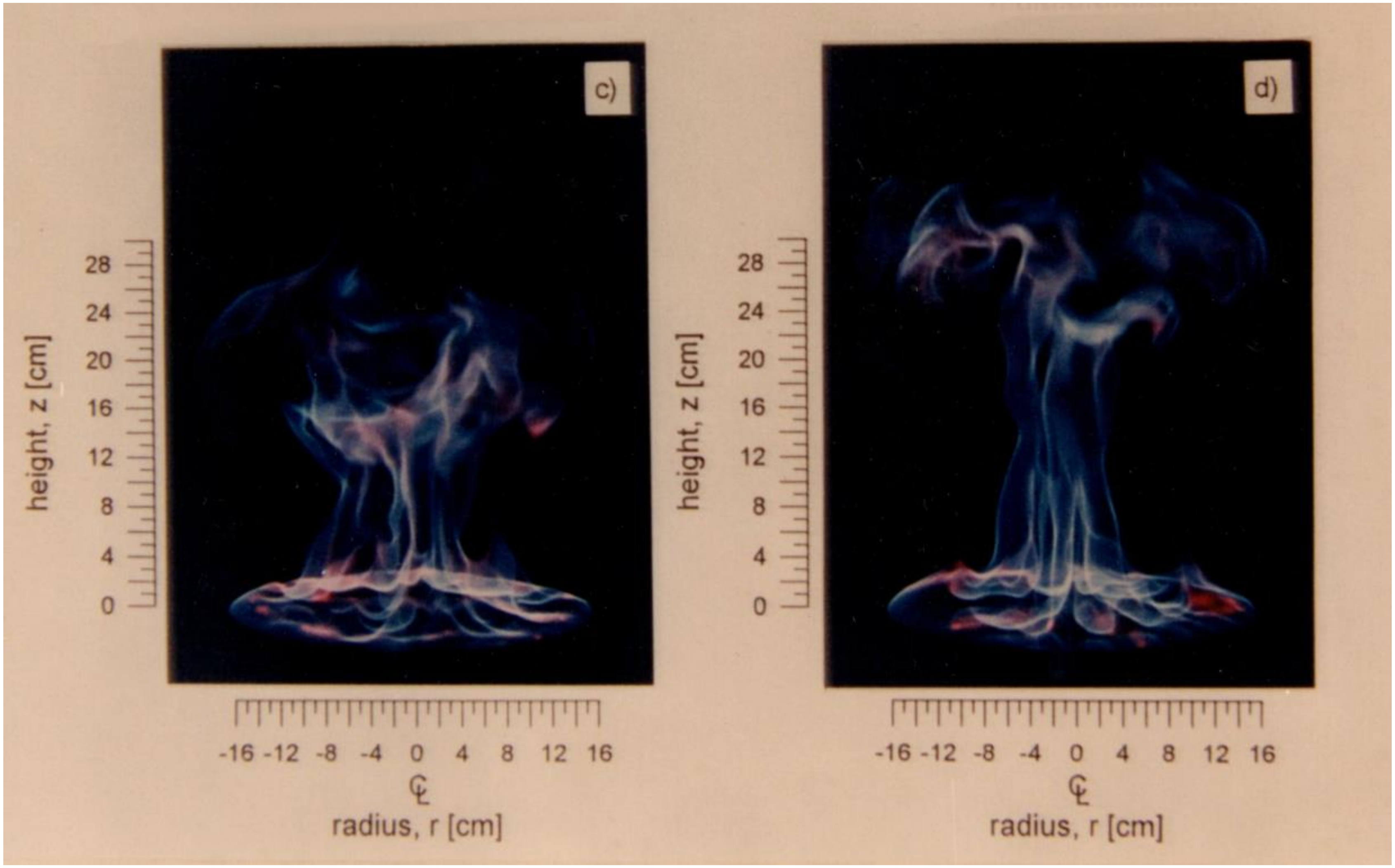
Methanol Pool Flame Pulsation



Pulsation cycle of fire

Frequency: 2.8 Hz

Methanol Pool Flame Pulsation



Pulsation cycle of fire

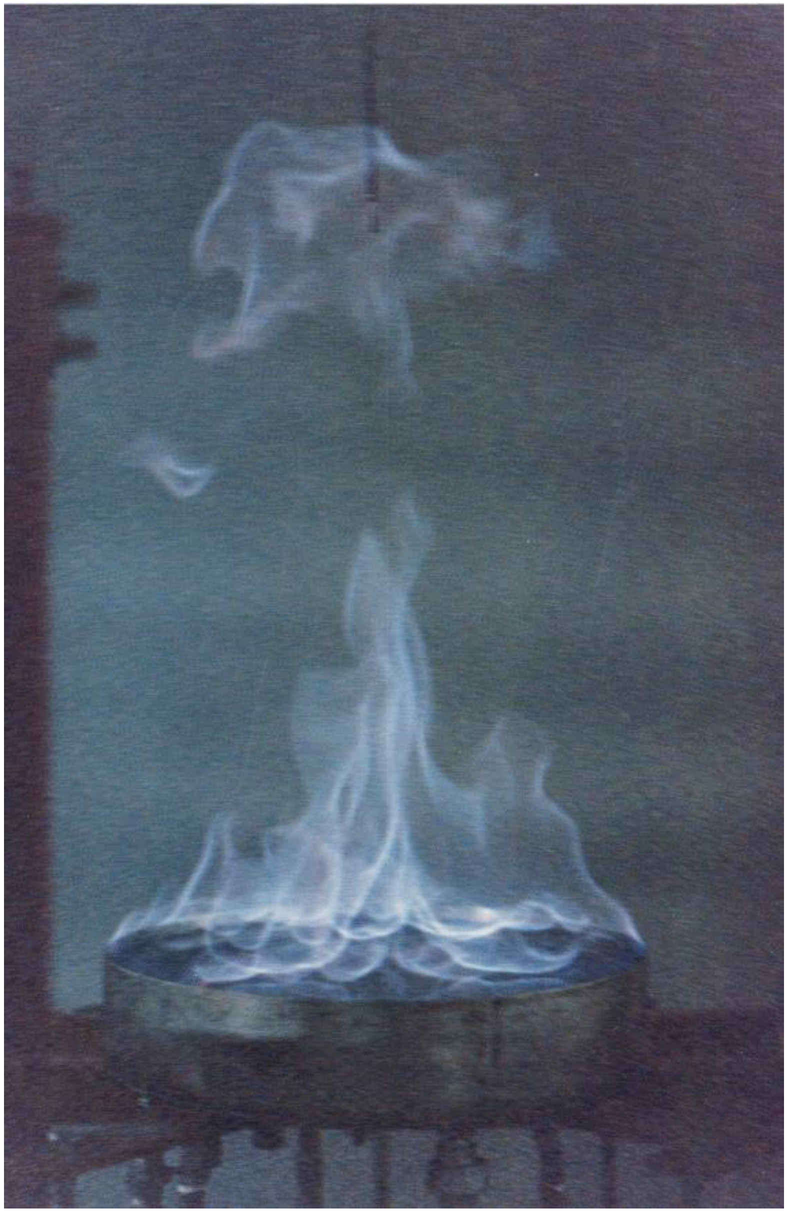
Frequency: 2.8 Hz

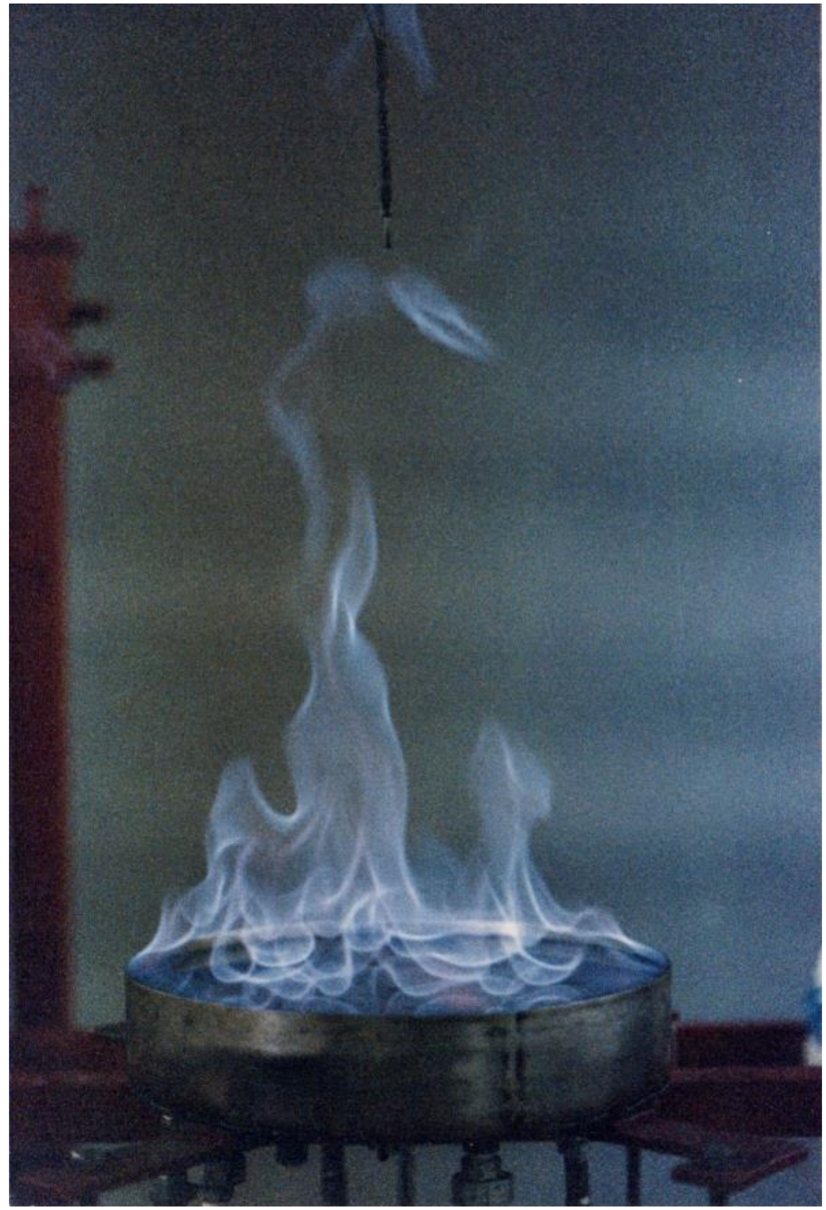
Methanol Flame Photography

Direct photography of luminous flame envelope

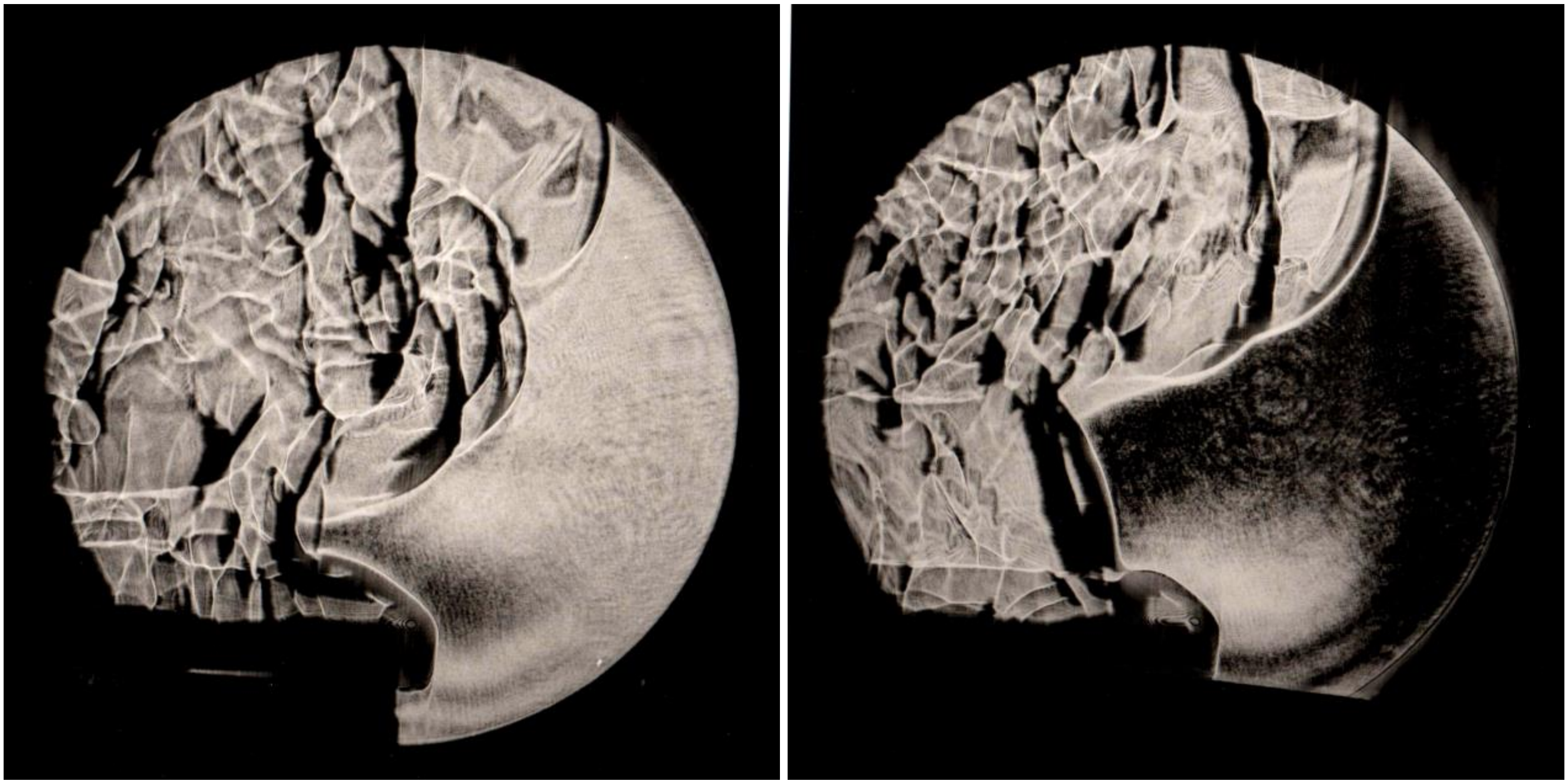
- macroscopic features of the fire flow field
  - vapor core
  - continuous flame zone
  - highly fluctuating regions of the fire
    - large scale structures characteristic of free burning fires are formed here
- visible fire pulsations
- track oscillatory behaviour

Methanol Pool Flame Structure

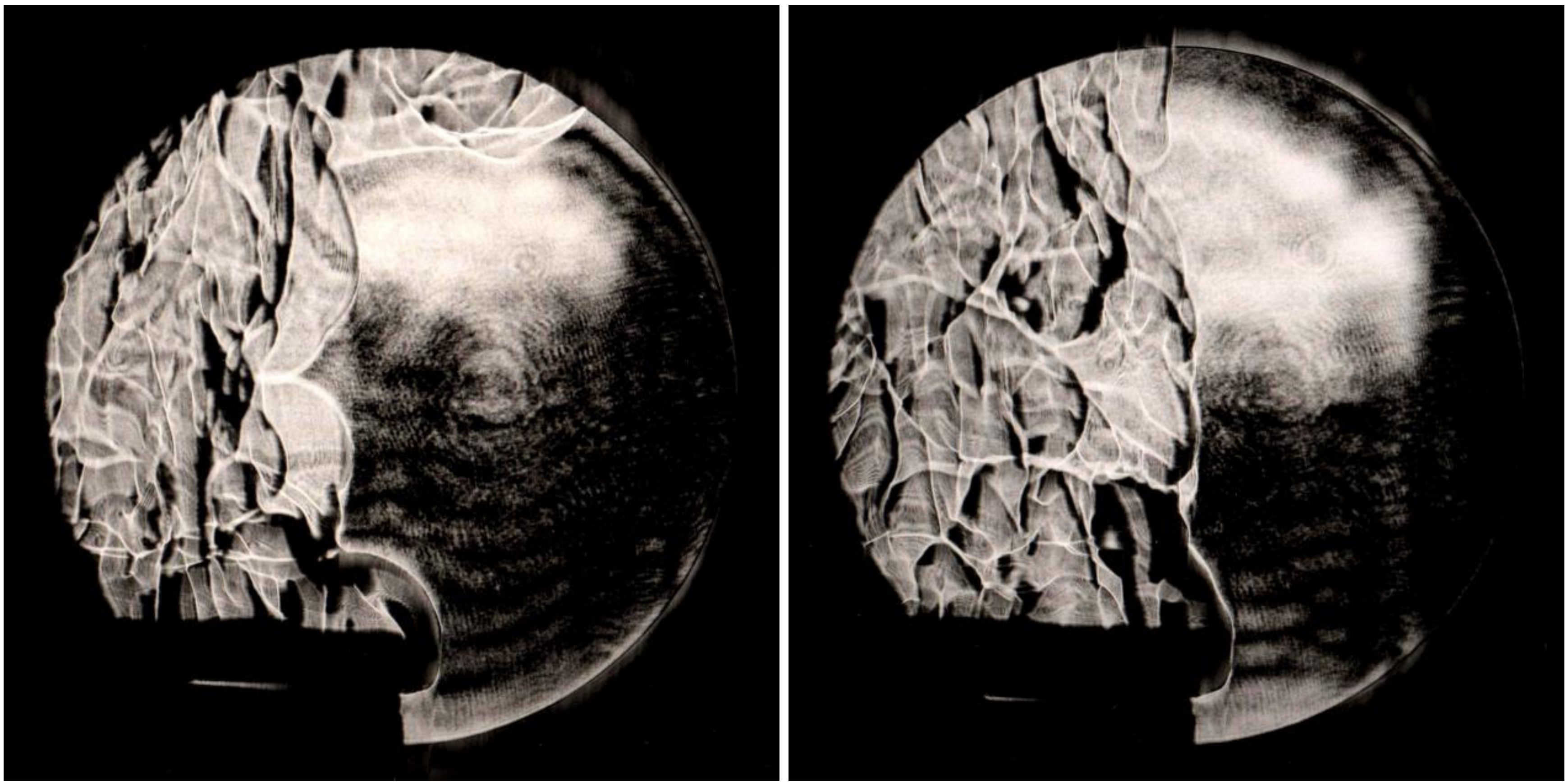




Methanol Pool Flame Schlieren



Methanol Pool Flame Schlieren



Simultaneous Velocity-Temperature

Radial and axial velocity

- Two component LDV
- Forward scatter configuration

Temperature

- Fine wire thermocouples
- 50 micron diameter, bare-wire Pt-Pt-10%Rh
- bead diameters in the range of 75-100 microns

- four channels of velocity and temperature data
- full time-series of discrete, instantaneous data
- 40,000 independent measurements at fixed sampling rate of 125 Hz

Simultaneous Velocity-Temperature

- time series ensemble-averaged
  - mean and rms values
  - correlation coefficients
  - turbulence time and length scales
  - autospectra of velocity and temperature
- estimation of turbulent parameters
  - turbulent kinetic energy and production
  - isotropic dissipation rate/mass,
  - turbulent Reynolds and Prandtl numbers
  - include contributions from large-scale vortical structures and smaller scales more classical turbulence

Waterloo Methanol Pool Flame

Measurements

- Data:
  - **Mean and rms values**: u-bar, u-rms (vertical direction); v-bar, v-rms (radial direction); T-bar, T-rms
  - **Turbulent fluxes**: uv (*rz*-Reynolds shear stress), uT (turbulent heat flux in vertical direction), vT (turbulent heat flux in radial direction)
  - **Integral time scales**: $T_{t,u}$, $T_{t,v}$, $T_{t,T}$

$$R_{uu}(\tau) = \frac{\overline{u'(t)\, u'(t+\tau)}}{\overline{u'(t)\, u'(t)}}$$ (one-point auto-correlation function)

$$T_{t,u} = \int_0^\infty R_{uu}(\tau) d\tau$$ (integral time scale)

Simultaneous Velocity-Temperature

Uncertainty Analysis

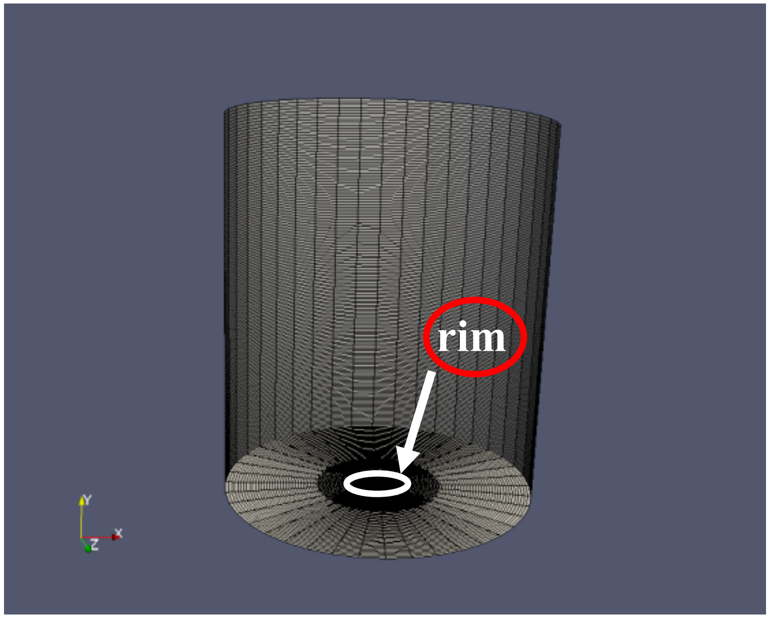
- mean and rms velocity: ± 5% at 95% confidence
- mean temperature: ± 5% at 95% confidence
- Reynolds stress : ± 15% at 95% confidence
- rms temperature and velocity-temperature correlations – unknown
  - depend on standard instrument error
  - unquantifiable error due to compensation for thermal inertia of the thermocouple no in situ compensation
  - temperature data digitally compensated
  - no correction for catalytic or radiation effects - less than 5%

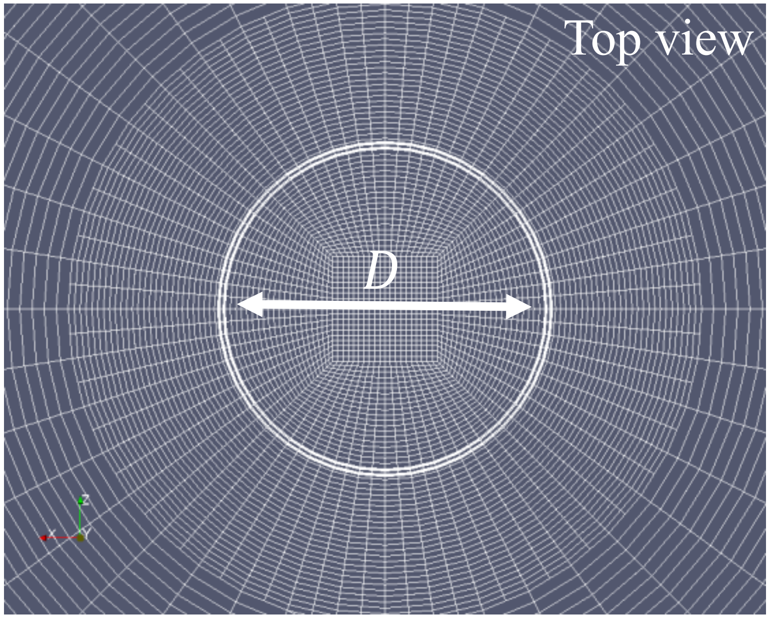
Case 3: Waterloo Methanol Pool Flame

- **Computational results**
  - G. Maragkos *et al.* (UGent)
  - A. Marchand *et al.* (UMD)
  - T. Sikanen *et al.* (VTT)

Computational Results

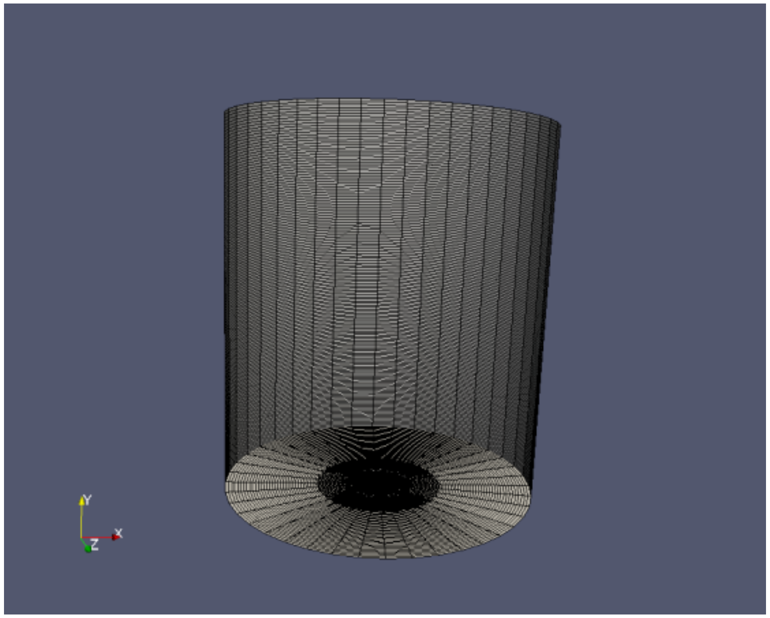
- **G. Maragkos *et al*. (UGent)**
  - FireFOAM, Version 2.2.x
  - Discretization
    - Computation domain: **1.5 m** × 1.8 m (cylindrical)
    - Domain discretization: 0.985 million cells; resolution: 0.5 cm in flame region
    - Angular space discretization: 72 solid angles

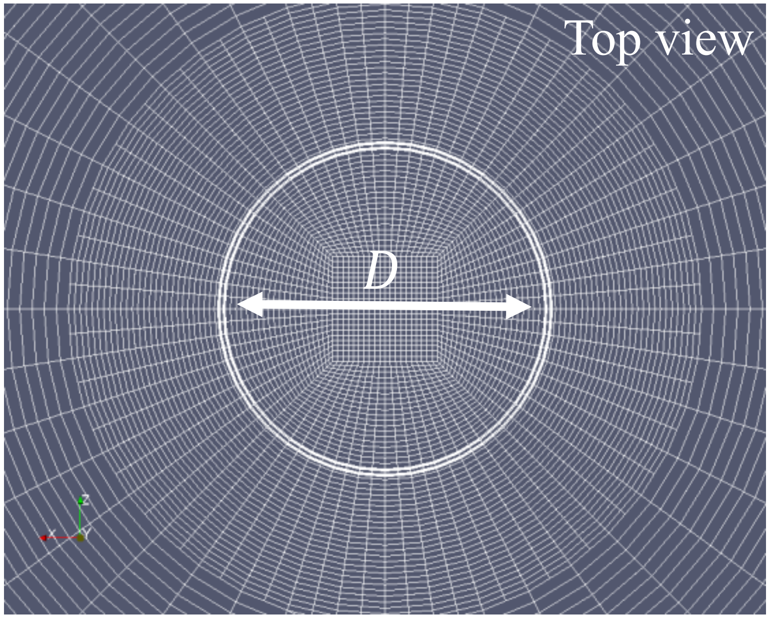




Computational Results

- **G. Maragkos *et al*. (UGent)**
  - Boundary conditions
    - Fuel inlet: prescribed mass flow rate; fixed temperature (T_{BP} = 338 K)
    - Open flow boundary conditions at south, side and north air boundaries





Computational Results

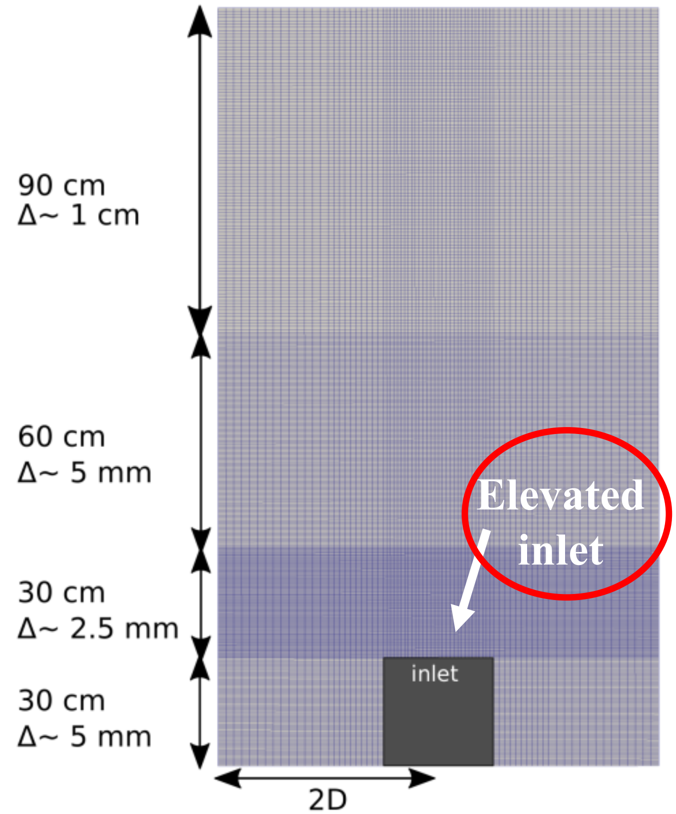
- **G. Maragkos *et al*. (UGent)**
  - SGS models
    - **Turbulence**: dynamic Smagorinsky
    - **Combustion**: modified Eddy Dissipation Concept (EDC)
    - **Radiation**: full RTE with Weighted-Sum-of-Grey-Gases (WSGG) model
      - Predicted global radiant fraction $\chi_{rad} \sim 16.4\%$

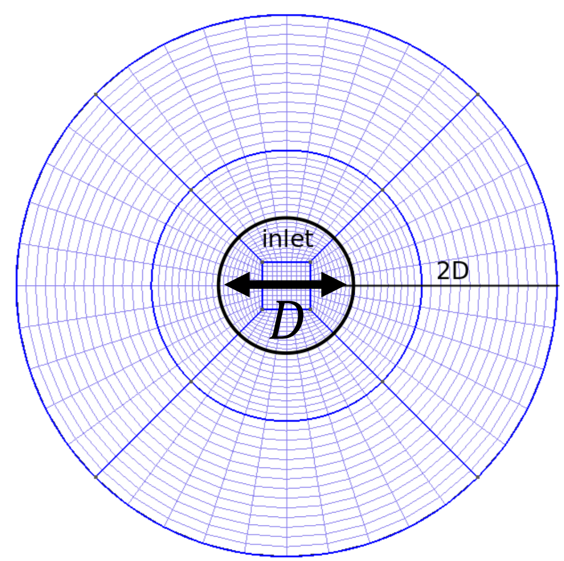
Computational Results

- **G. Maragkos *et al*. (UGent)**
  - Computational cost
    - Simulated time: 65 s
    - CPU cost: (103 hours) × (24 processors) = 2,472 CPU-hours (38 CPU-hours/simulated s)
  - Maturity level
    - New iteration of recently completed project/published work (Maragkos *et al*., *Combust. Flame* **181** (2017) 22-38)

Computational Results

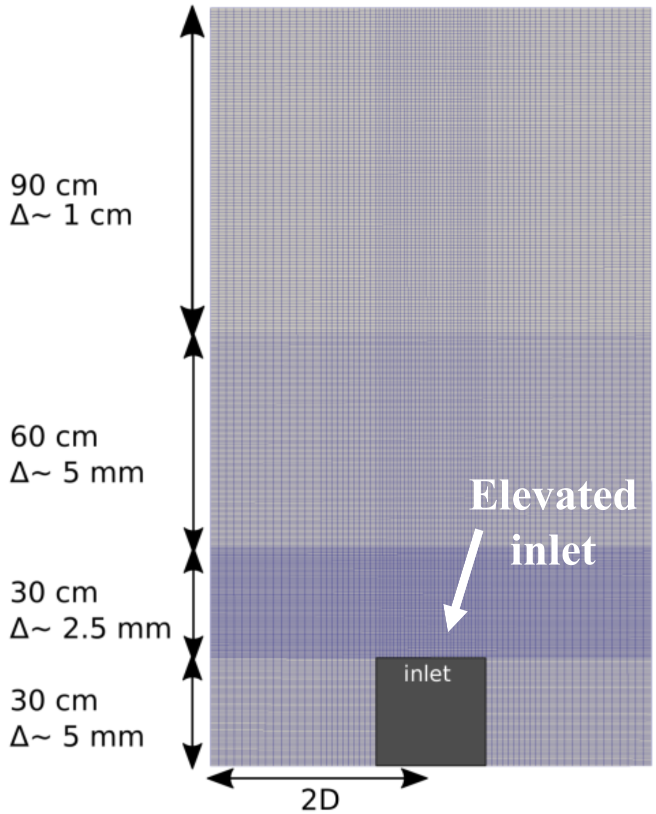
- **A. Marchand *et al.* (UMD)**
  - FireFOAM, Version dev
  - Discretization
    - Computation domain: **1.2 m** × 1.8 m (cylindrical)
    - Domain discretization: 0.561 million cells; resolution: **1 cm** × **0.25 cm** in flame base region
    - Angular space discretization: **16** solid angles

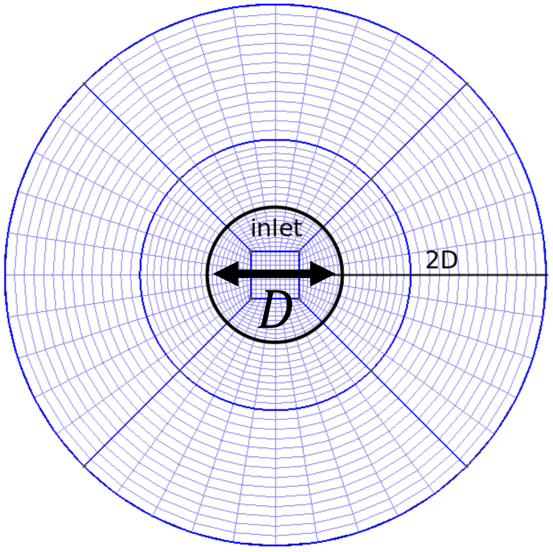




Computational Results

- **A. Marchand *et al*. (UMD)**
  - Boundary conditions
    - Fuel inlet: prescribed mass flow rate; fixed temperature (T_{BP} = 338 K)
    - Open flow boundary conditions at south, side and north air boundaries





Computational Results

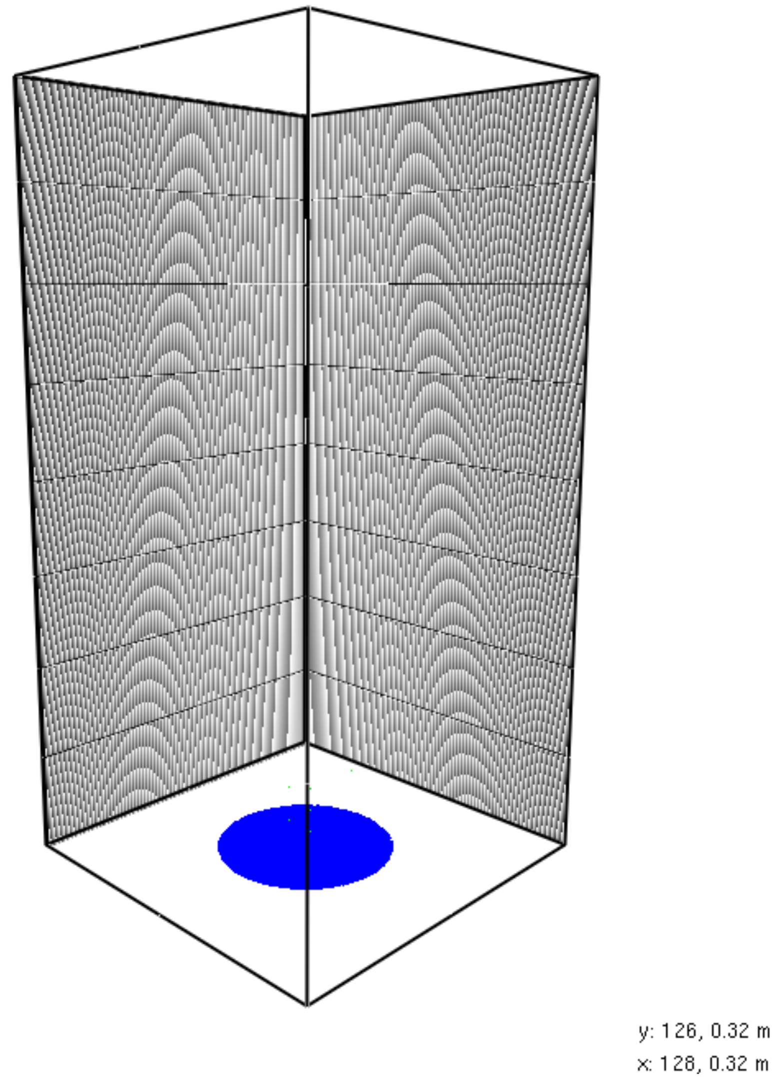
- **A. Marchand *et al*. (UMD)**
  - SGS models
    - **Turbulence**: dynamic *k*-equation
    - **Combustion**: Eddy Dissipation Model (EDM)
    - **Radiation**: emission-only RTE with prescribed global radiant fraction ($\chi_{rad} = 18\%$)

Computational Results

- **A. Marchand *et al*. (UMD)**
  - Computational cost
    - Simulated time: 60 s
    - CPU cost: (90 hours) × (60 processors) = 5,400 CPU-hours (90 CPU-hours/simulated s)
  - Maturity level
    - New project, work-in-progress

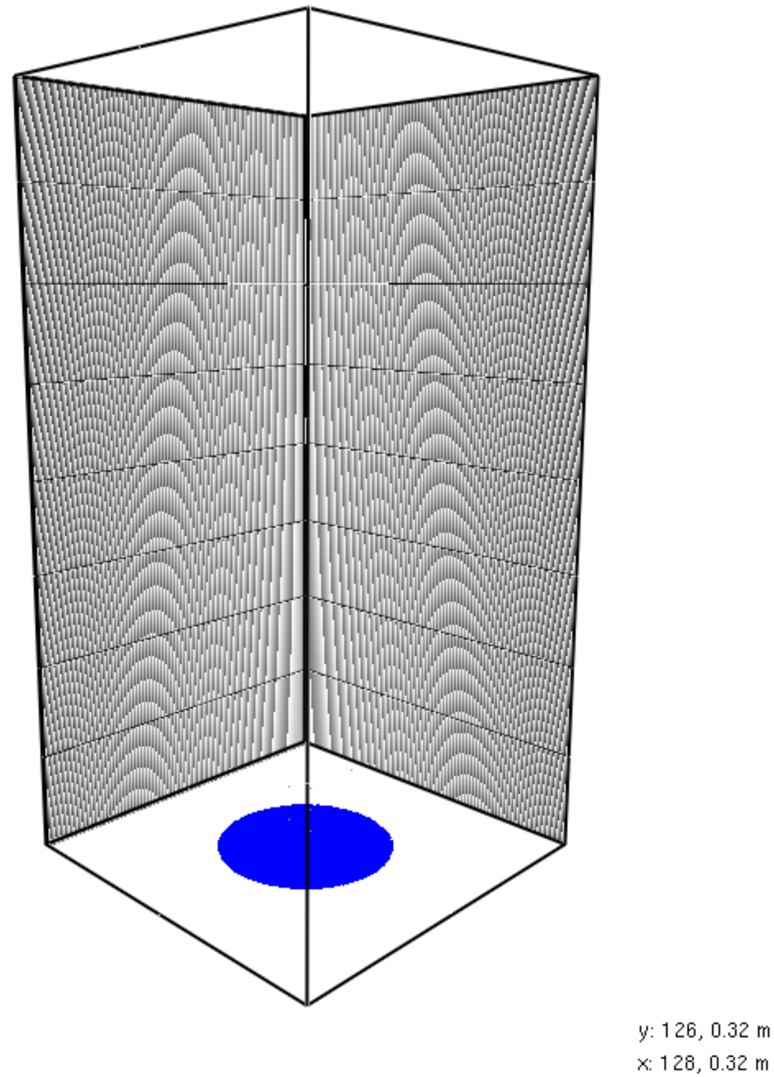
Computational Results

- **T. Sikanen *et al.* (VTT)**
  - FDS, Version 6.5.3
  - Discretization
    - Computation domain: **0.64 m** × **0.64 m** × 1.28 m (rectangular)
    - Domain discretization: **33.554** million cells; resolution: **0.25 cm** (uniform)
    - Angular space discretization: 104 solid angles



Computational Results

- **T. Sikanen *et al.* (VTT)**
  - Boundary conditions
    - Fuel inlet: **calculated** mass flow rate (1D evaporation model); fixed temperature (T_{BP} = 338 K)
      - Predicted fuel evaporation rate under-estimated by a factor ~ 2
    - Open flow boundary conditions at south, side and north air boundaries



Computational Results

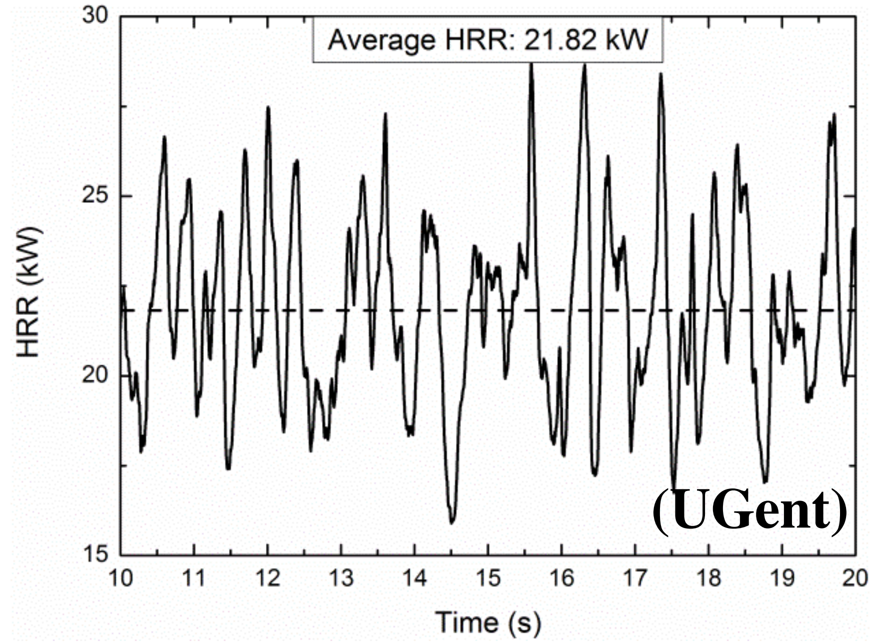
- **T. Sikanen *et al.* (VTT)**
  - SGS models
    - **Turbulence**: Modified Deardorff
    - **Combustion**: Eddy Dissipation Model (EDM)
    - **Radiation**: emission-only RTE with prescribed global radiant fraction (χ_{rad} = 17%)

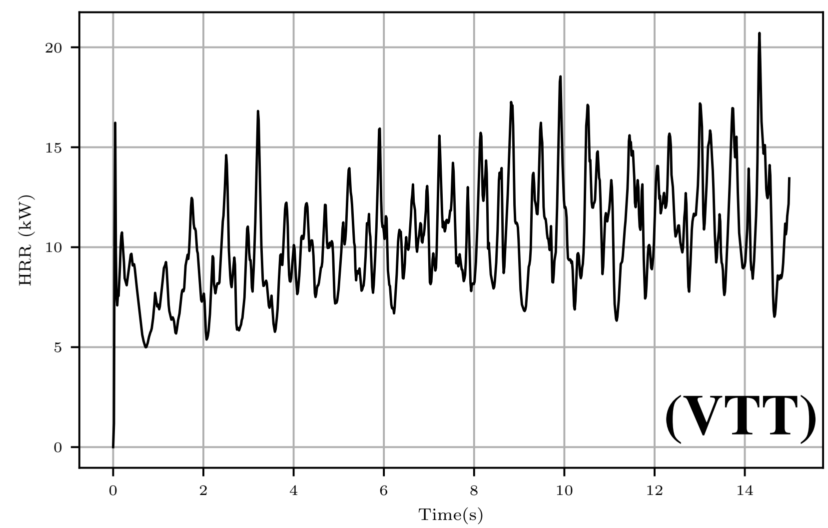
Computational Results

- **T. Sikanen *et al.* (VTT)**
  - Computational cost
    - Simulated time: **15 s**
    - CPU cost: (130 hours) × (32 processors) = 4,160 CPU-hours (416 CPU-hours/simulated s)
  - Maturity level
    - New project, work-in-progress

Waterloo Methanol Pool Flame

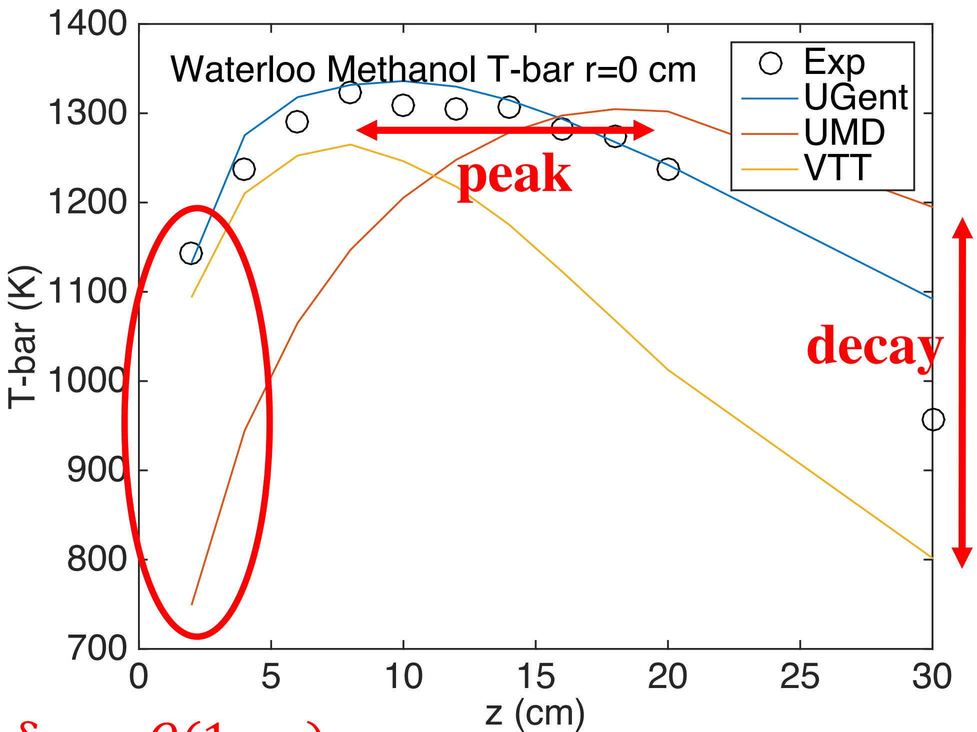
- **Heat release rate**
  - 21.8 kW (UGent), 22.6 kW (UMD), ~ **13 kW** (VTT)
- **Flame dynamics**
  - Puffing frequency:
    - 2.8 Hz (UGent)
    - 2.2 Hz (UMD)
    - ~ 3 Hz (VTT)
  - Movies (UMD) (VTT)



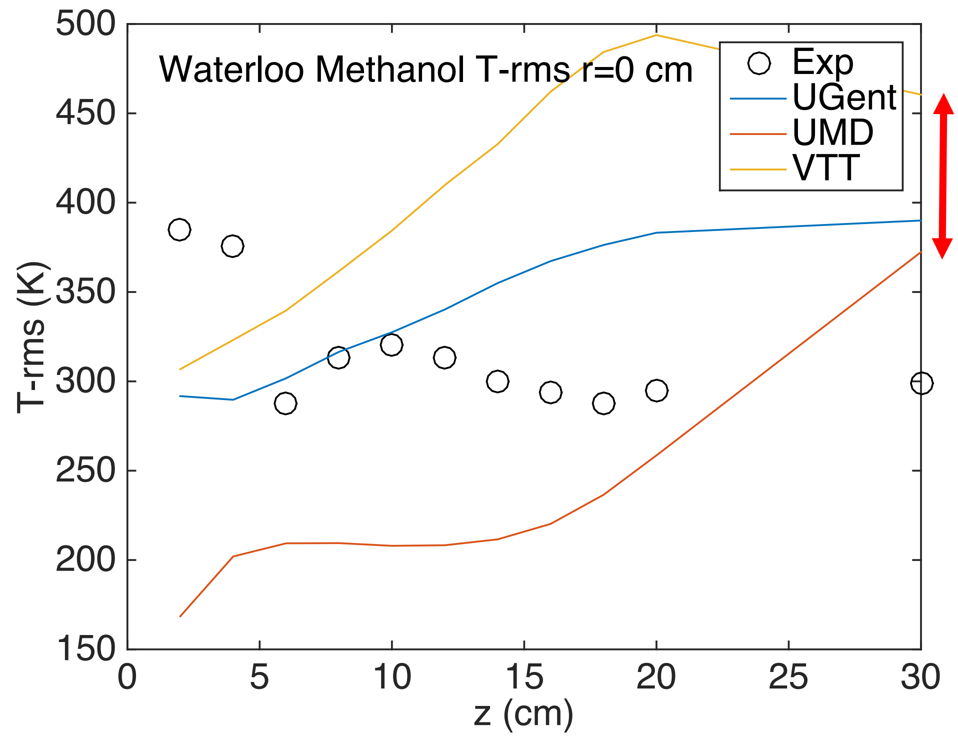


Waterloo Methanol Pool Flame

- **Centerline variations**
  - Temperature

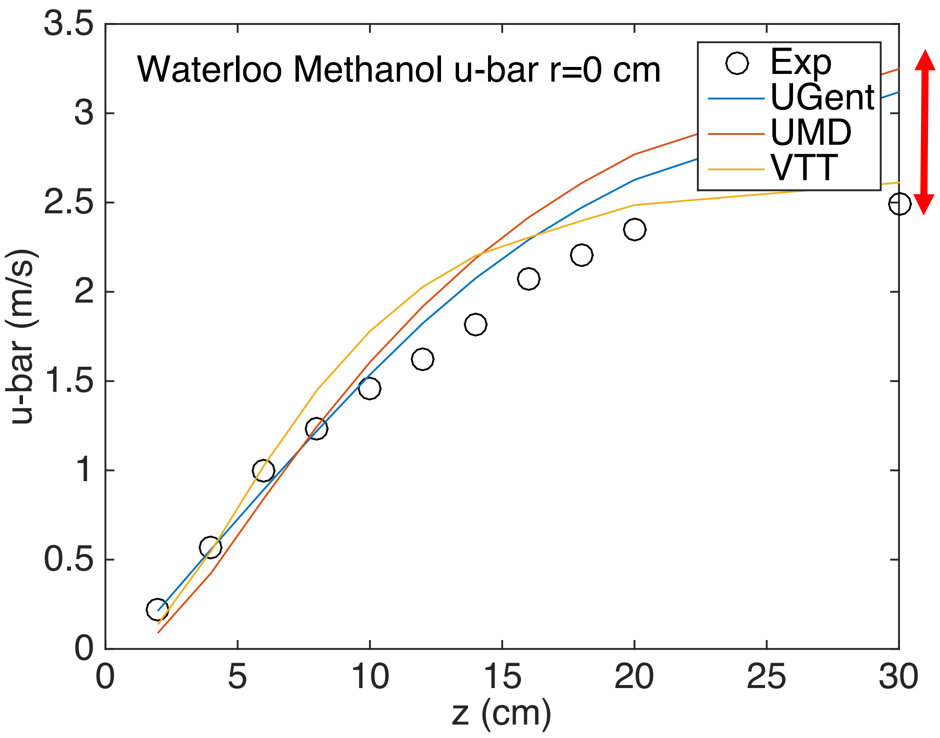


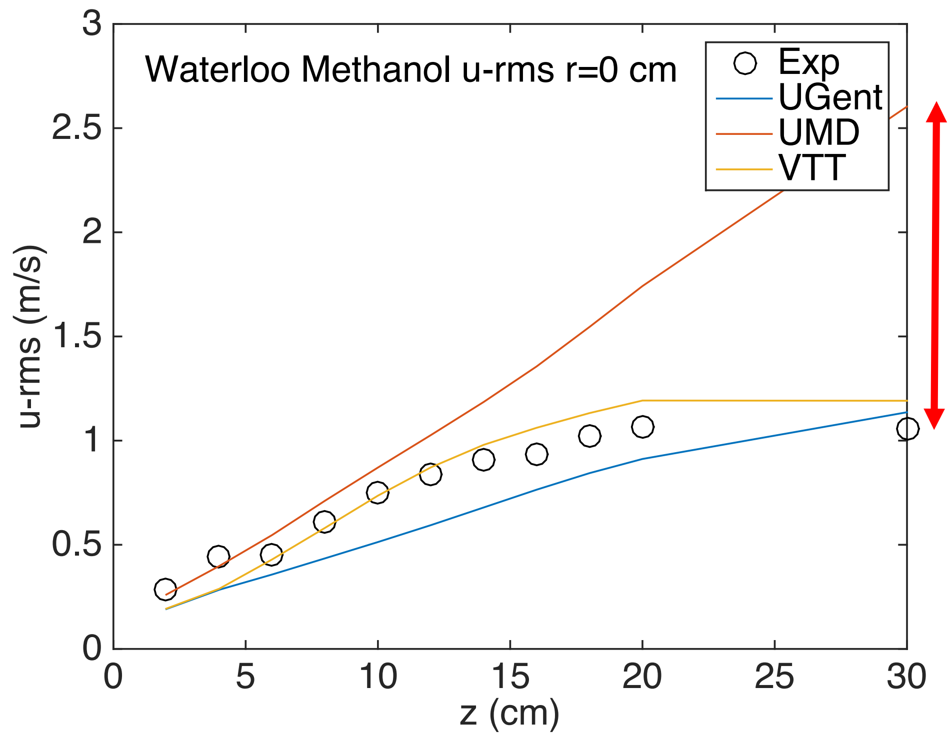
$\delta_{BL} = O(1\ \text{cm})$



Waterloo Methanol Pool Flame

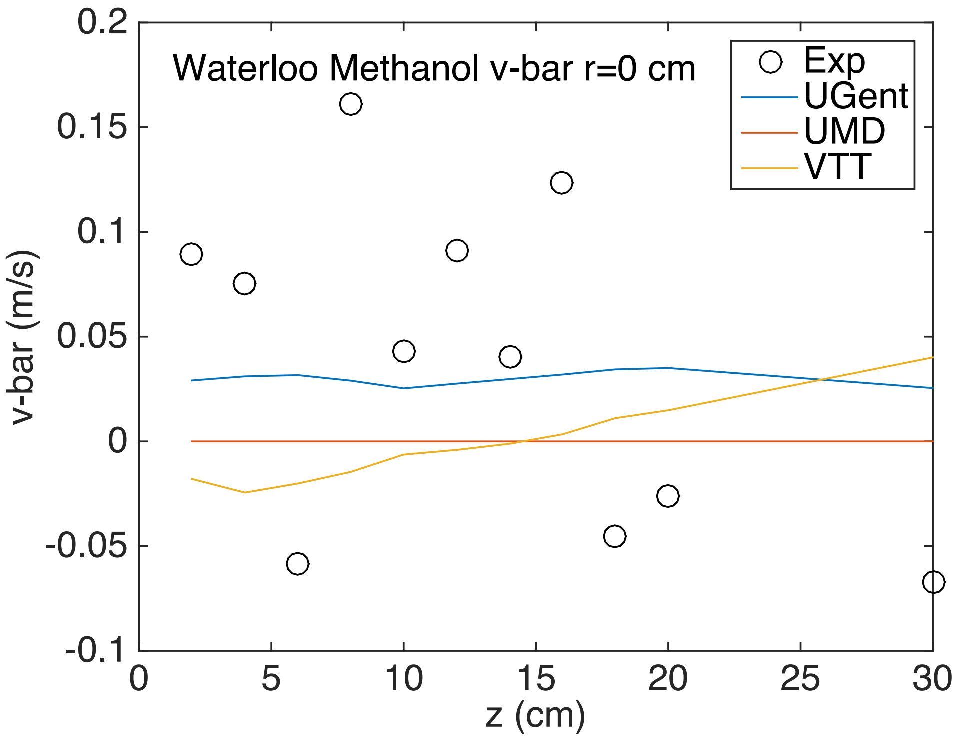
- **Centerline variations**
  - Vertical velocity



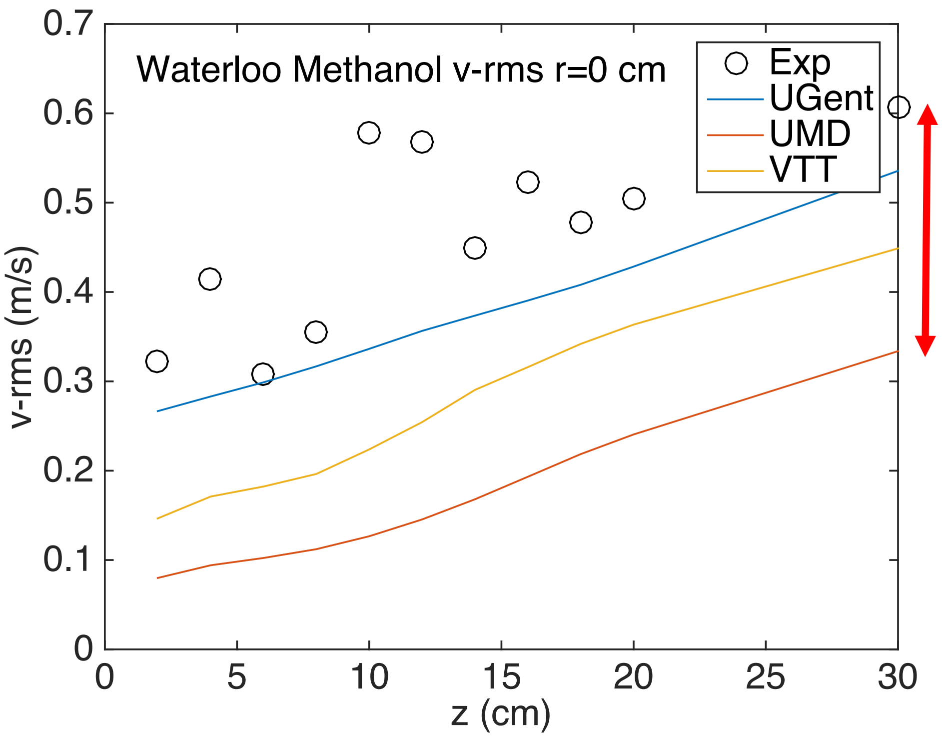


Waterloo Methanol Pool Flame

- **Centerline variations**
  - Radial velocity

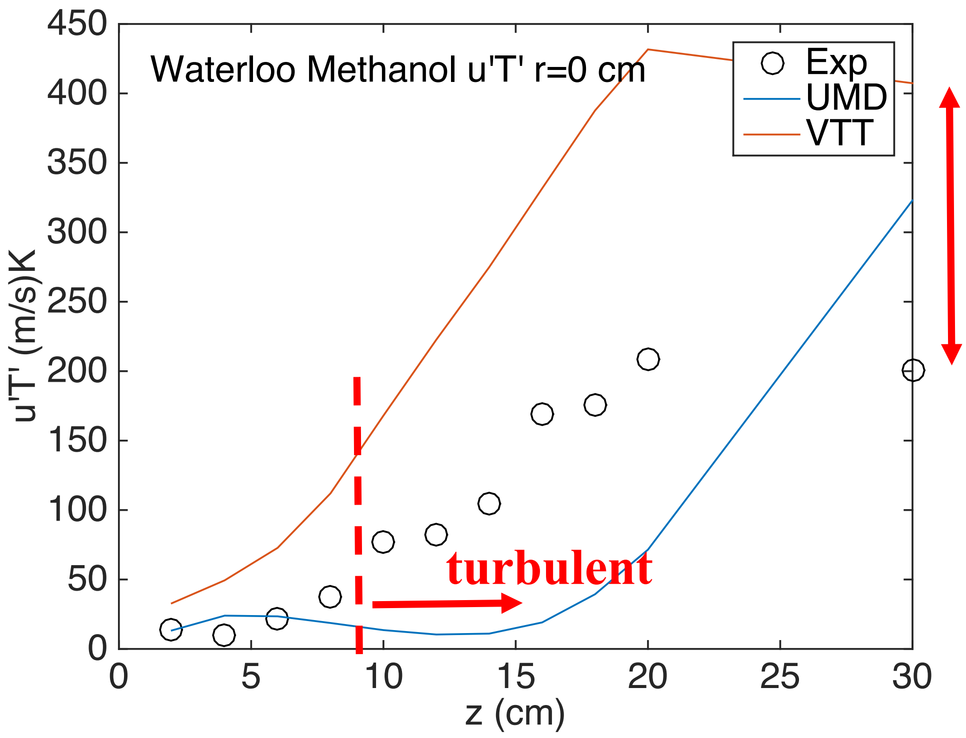


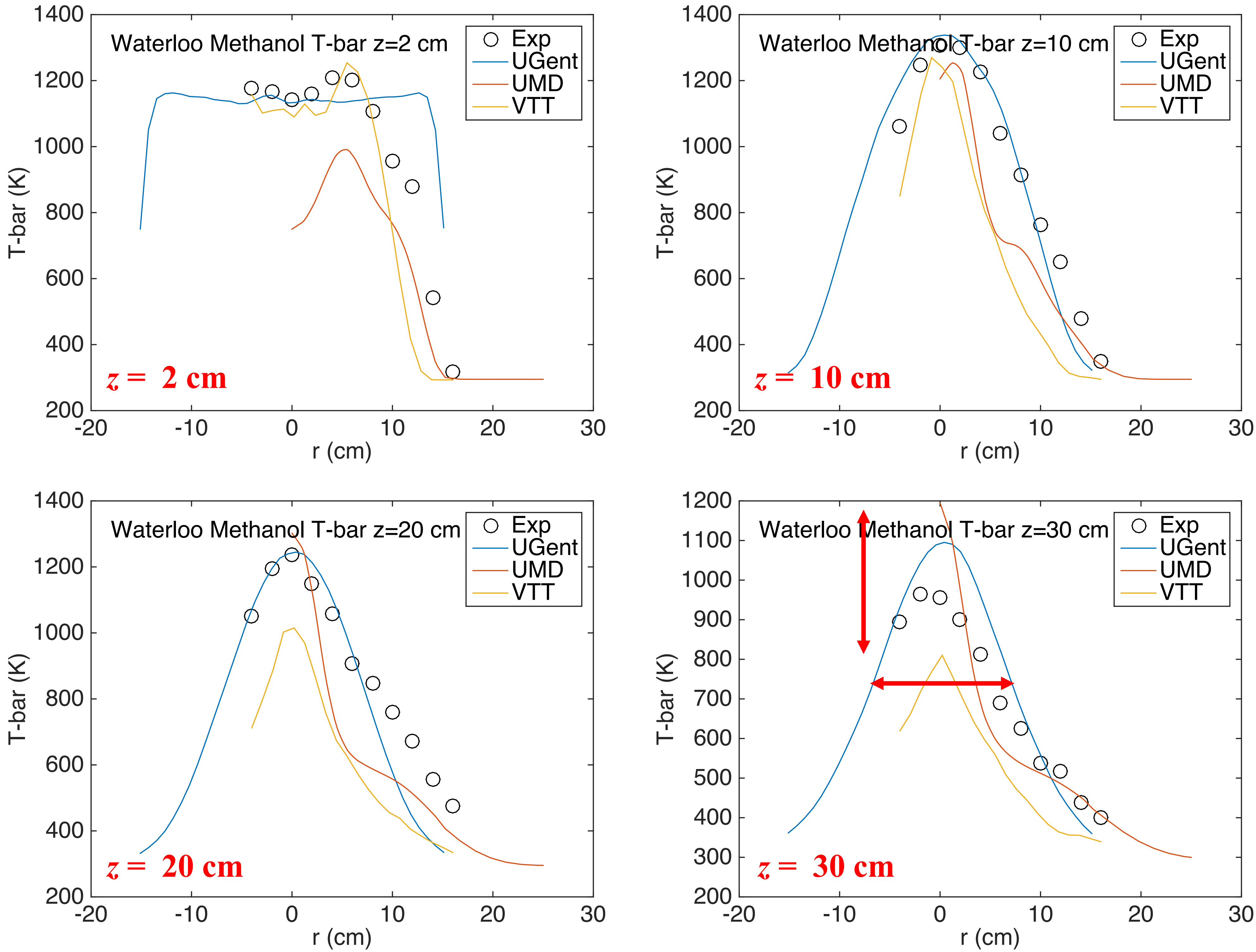
(should be 0, gives a measure of error)



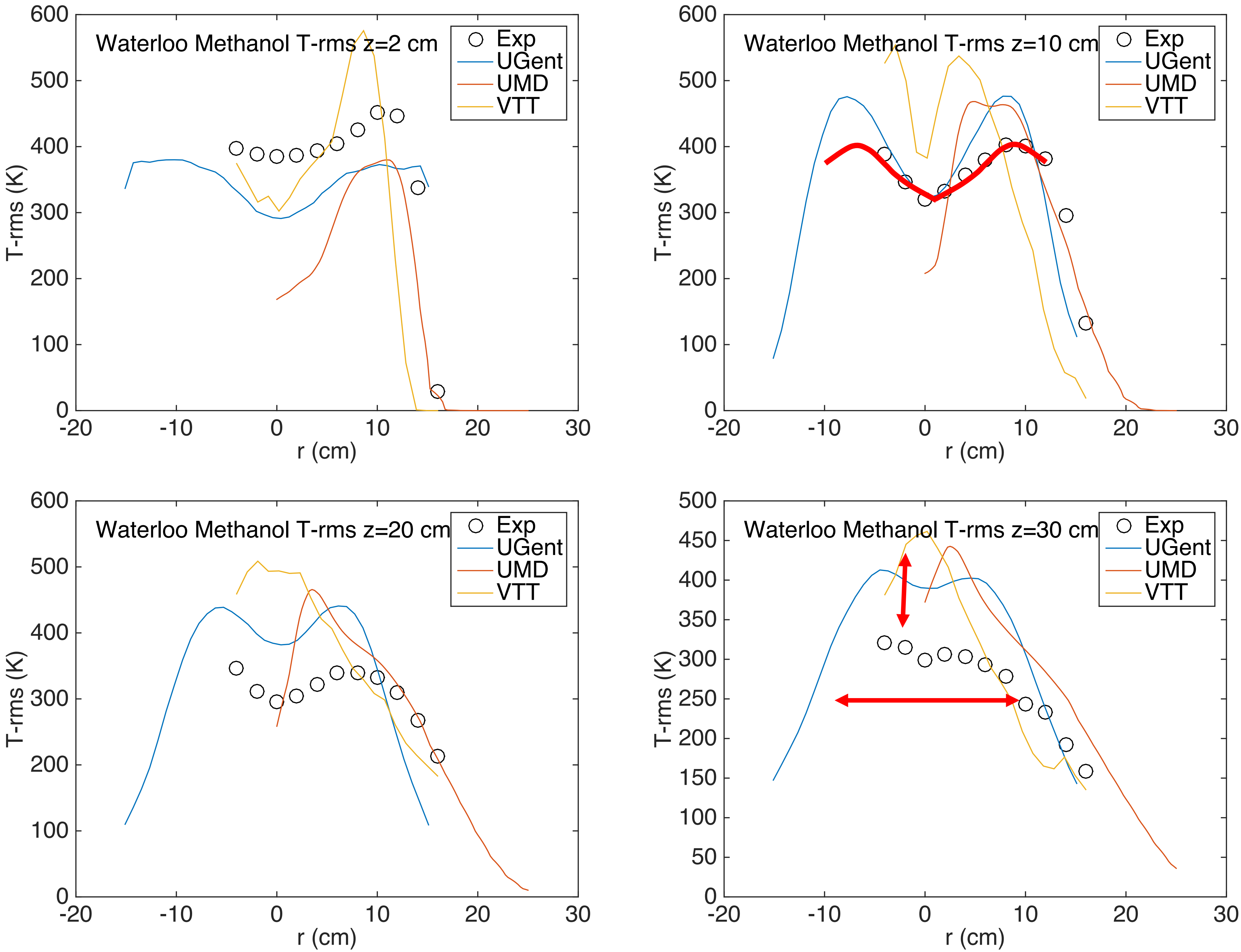
Waterloo Methanol Pool Flame

- **Centerline variations**
  - Turbulent heat flux in vertical direction

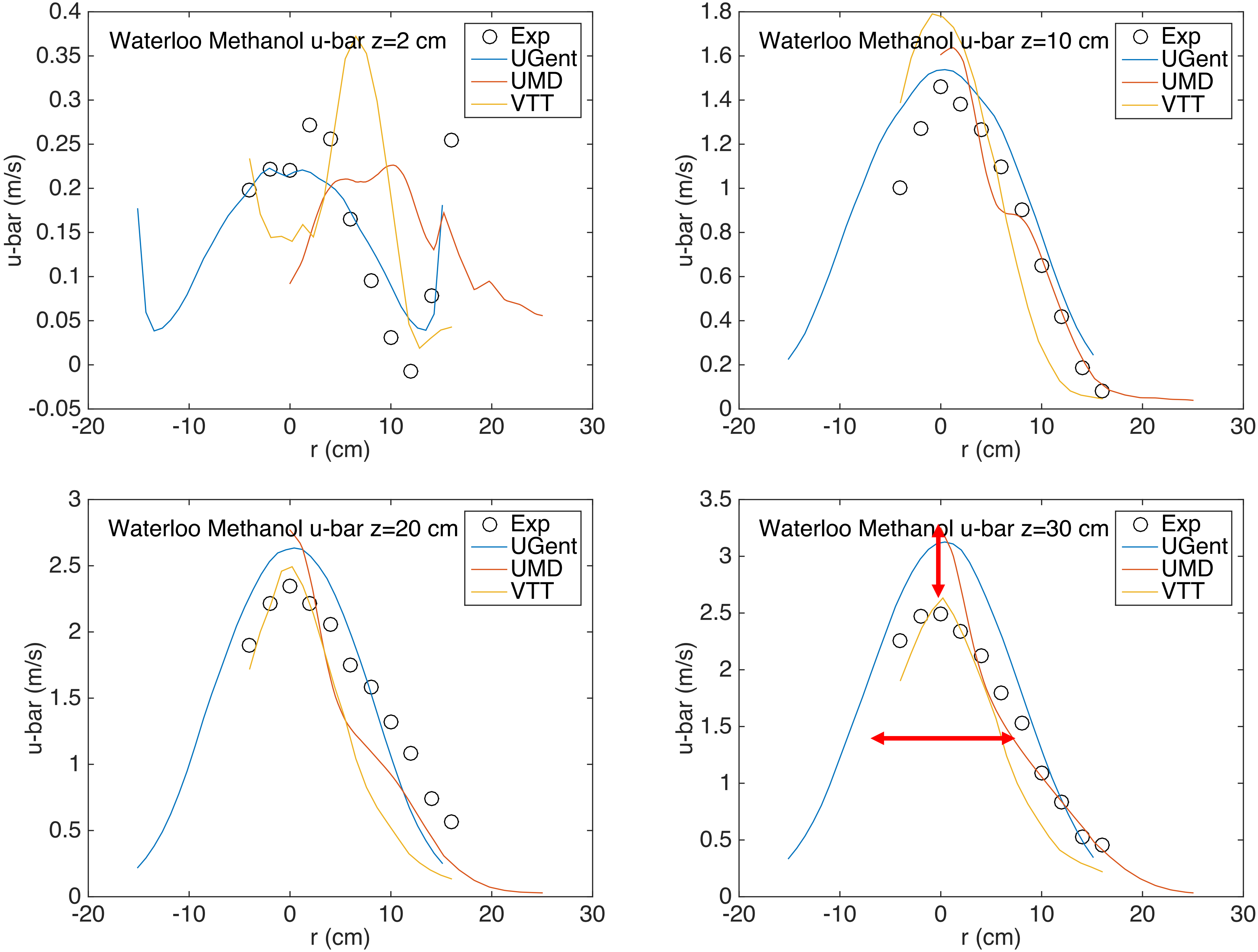




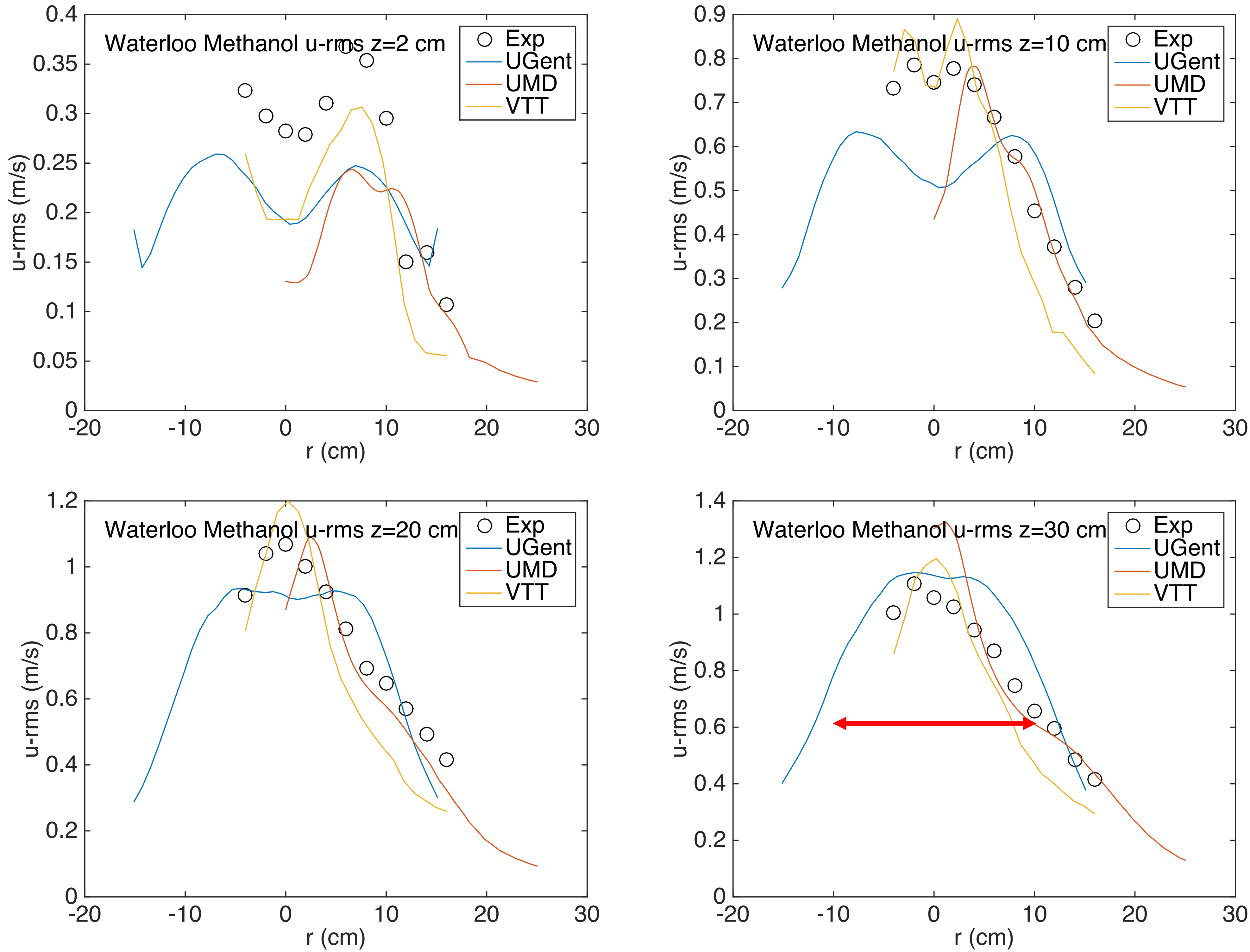
Waterloo Methanol T-bar z=2 cm
Waterloo Methanol T-bar z=10 cm
Waterloo Methanol T-bar z=20 cm
Waterloo Methanol T-bar z=30 cm
Exp
UGent
UMD
VTT
T-bar (K)
r (cm)
z = 2 cm
z = 10 cm
z = 20 cm
z = 30 cm

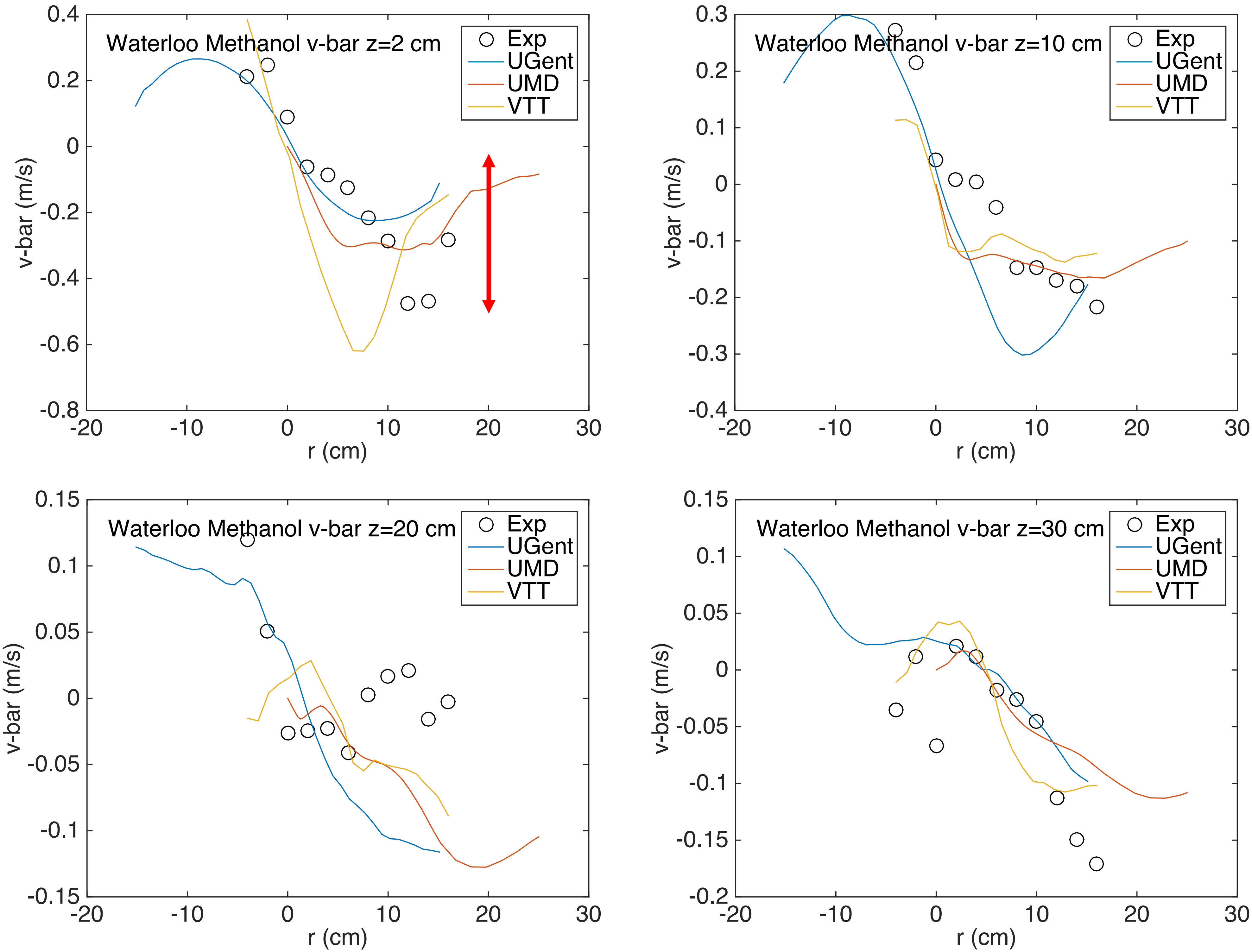


Waterloo Methanol T-rms z=2 cm
Exp
UGent
UMD
VTT
T-rms (K)
r (cm)
Waterloo Methanol T-rms z=10 cm
Exp
UGent
UMD
VTT
T-rms (K)
r (cm)
Waterloo Methanol T-rms z=20 cm
Exp
UGent
UMD
VTT
T-rms (K)
r (cm)
Waterloo Methanol T-rms z=30 cm
Exp
UGent
UMD
VTT
T-rms (K)
r (cm)

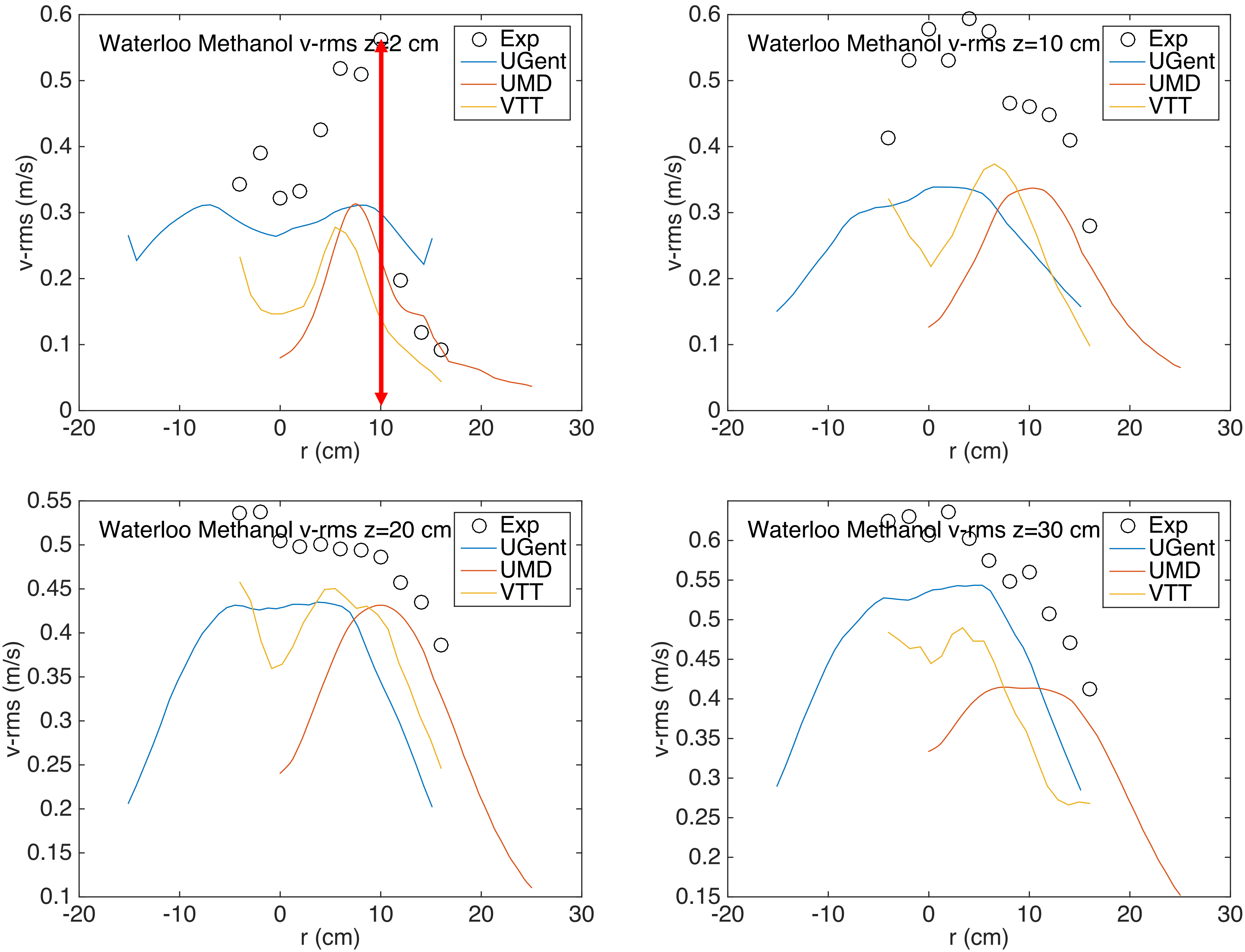


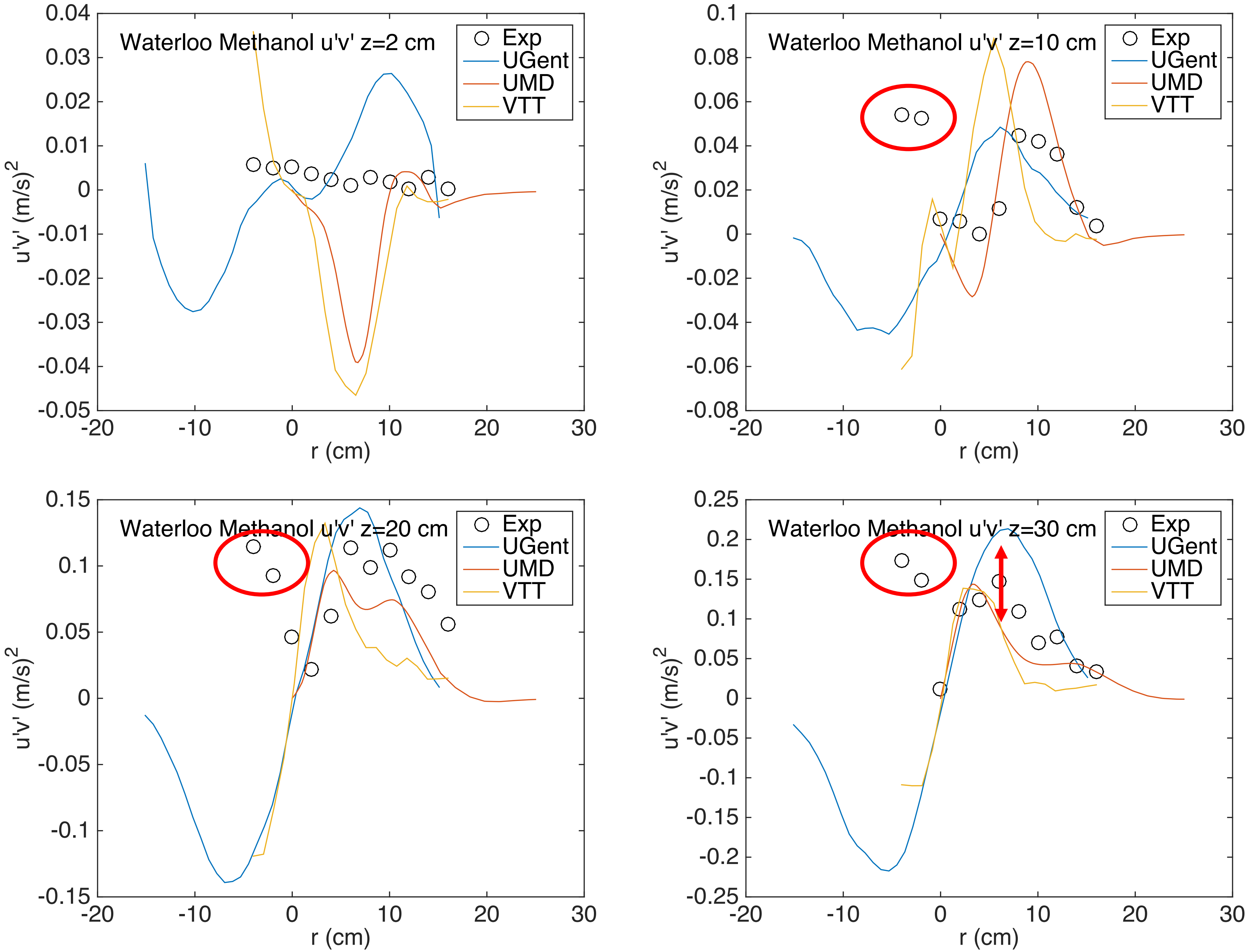
Waterloo Methanol u-bar z=2 cm
Exp
UGent
UMD
VTT
u-bar (m/s)
r (cm)
Waterloo Methanol u-bar z=10 cm
Exp
UGent
UMD
VTT
u-bar (m/s)
r (cm)
Waterloo Methanol u-bar z=20 cm
Exp
UGent
UMD
VTT
u-bar (m/s)
r (cm)
Waterloo Methanol u-bar z=30 cm
Exp
UGent
UMD
VTT
u-bar (m/s)
r (cm)


Waterloo Methanol u-rms z=2 cm
Waterloo Methanol u-rms z=10 cm
Waterloo Methanol u-rms z=20 cm
Waterloo Methanol u-rms z=30 cm
Exp
UGent
UMD
VTT
u-rms (m/s)
r (cm)

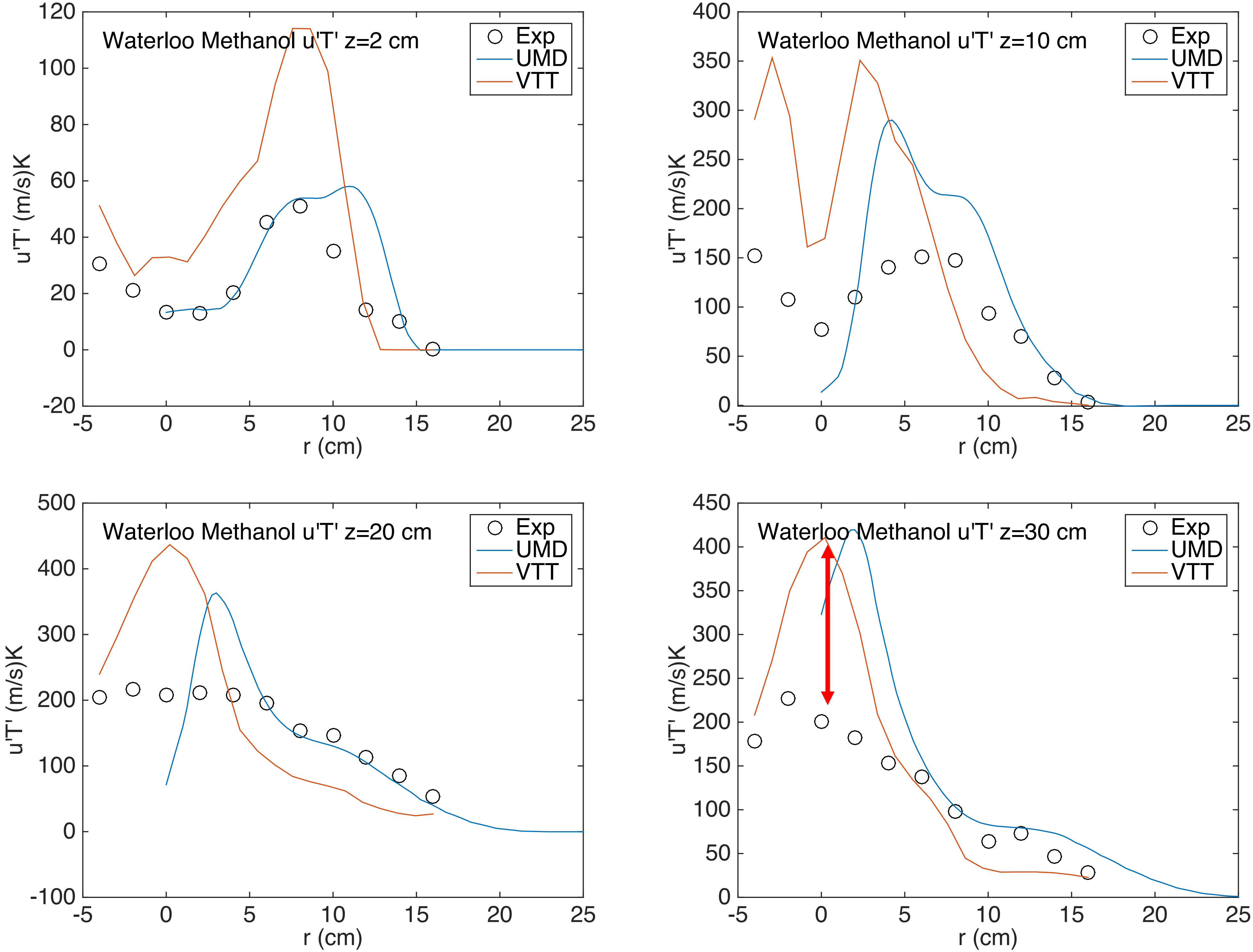


Waterloo Methanol v-bar z=2 cm
Waterloo Methanol v-bar z=10 cm
Waterloo Methanol v-bar z=20 cm
Waterloo Methanol v-bar z=30 cm
Exp
UGent
UMD
VTT
v-bar (m/s)
r (cm)

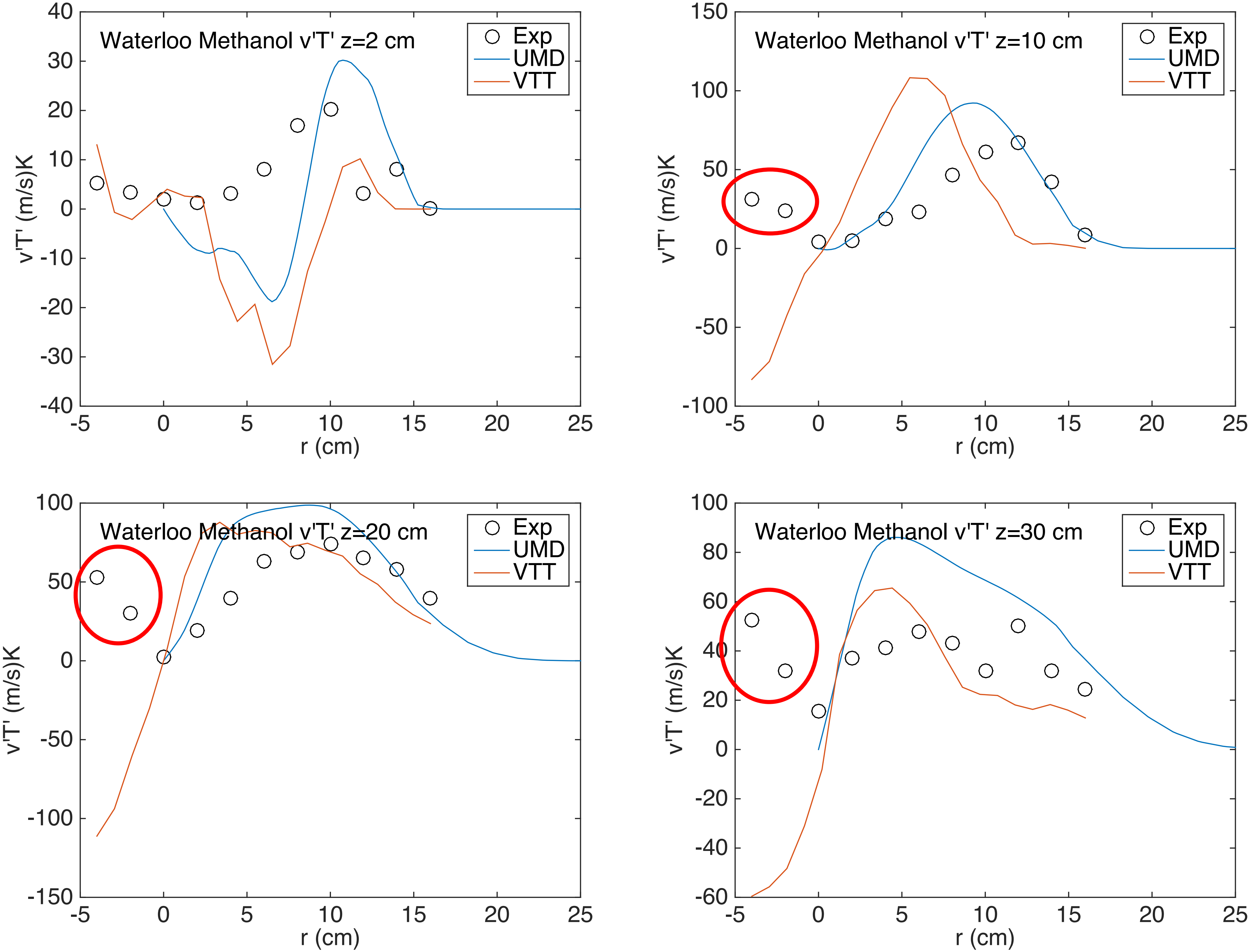

Waterloo Methanol v-rms z=2 cm
Waterloo Methanol v-rms z=10 cm
Waterloo Methanol v-rms z=20 cm
Waterloo Methanol v-rms z=30 cm
Exp
UGent
UMD
VTT
v-rms (m/s)
r (cm)



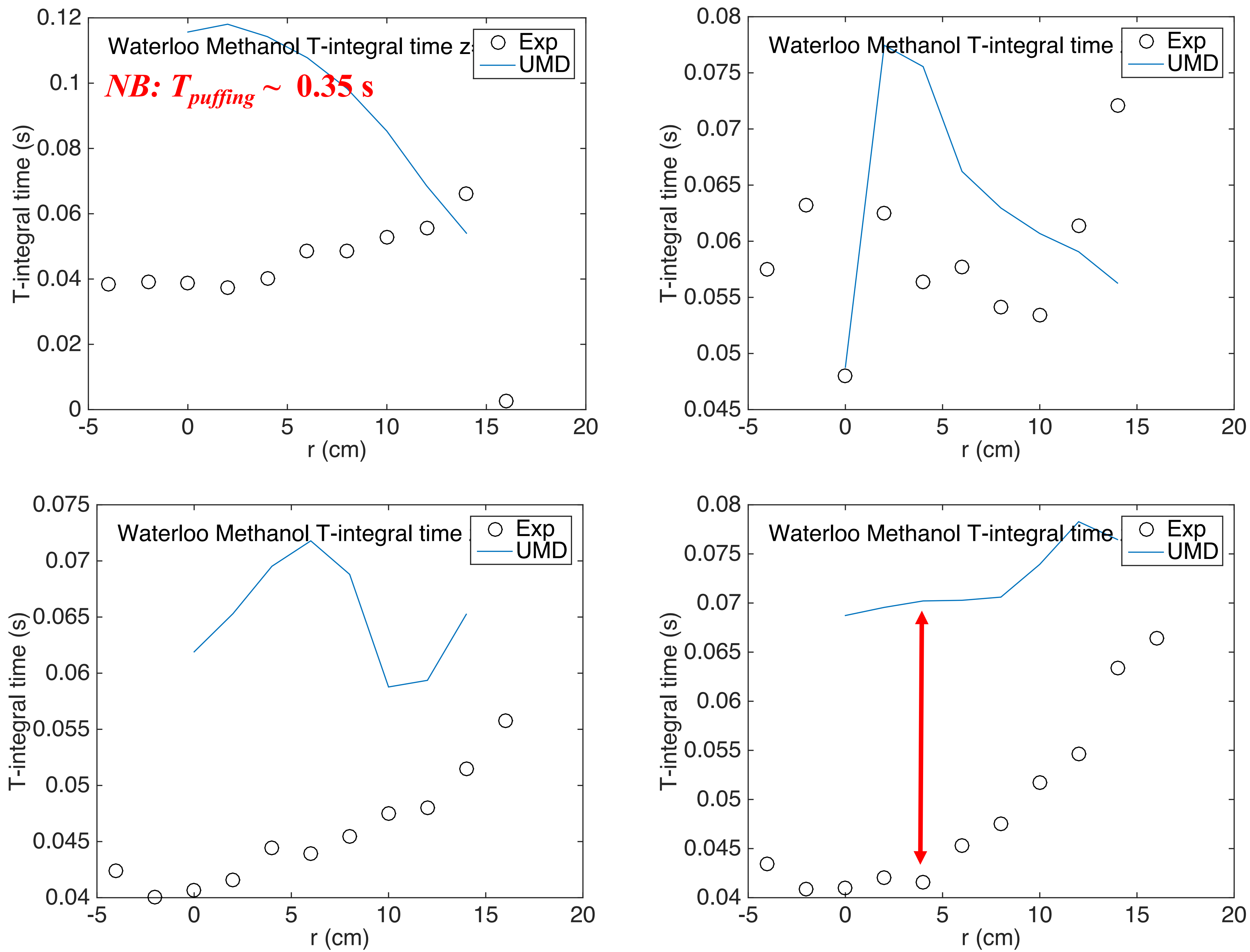
Waterloo Methanol u'v' z=2 cm
Waterloo Methanol u'v' z=10 cm
Waterloo Methanol u'v' z=20 cm
Waterloo Methanol u'v' z=30 cm
Exp
UGent
UMD
VTT
u'v' (m/s)^2
r (cm)



Waterloo Methanol u'T' z=2 cm
Exp
UMD
VTT
u'T' (m/s)K
r (cm)
120
100
80
60
40
20
0
-20
-5
0
5
10
15
20
25
Waterloo Methanol u'T' z=10 cm
Exp
UMD
VTT
u'T' (m/s)K
r (cm)
400
350
300
250
200
150
100
50
0
Waterloo Methanol u'T' z=20 cm
Exp
UMD
VTT
u'T' (m/s)K
r (cm)
500
400
300
200
100
0
-100
Waterloo Methanol u'T' z=30 cm
Exp
UMD
VTT
u'T' (m/s)K
r (cm)
450
400
350
300
250
200
150
100
50
0



Waterloo Methanol v'T' z=2 cm
Exp
UMD
VTT
v'T' (m/s)K
r (cm)
Waterloo Methanol v'T' z=10 cm
Exp
UMD
VTT
v'T' (m/s)K
r (cm)
Waterloo Methanol v'T' z=20 cm
Exp
UMD
VTT
v'T' (m/s)K
r (cm)
Waterloo Methanol v'T' z=30 cm
Exp
UMD
VTT
v'T' (m/s)K
r (cm)



Waterloo Methanol T-integral time z
NB: $T_{puffing}$ ~ 0.35 s
Exp
UMD
T-integral time (s)
r (cm)
Waterloo Methanol T-integral time
Exp
UMD
T-integral time (s)
r (cm)
Waterloo Methanol T-integral time
Exp
UMD
T-integral time (s)
r (cm)
Waterloo Methanol T-integral time
Exp
UMD
T-integral time (s)
r (cm)

Conclusions

- **Computational results**
  - Accuracy of UGent solution is good (both qualitatively and quantitatively)
    - *Question*: is this good performance due to computational resolution or to modified SGS models?
  - Accuracy of UMD and VTT solutions is not as good (qualitatively OK but quantitatively inaccurate)
    - Accuracy of UMD solution is limited by insufficient grid resolution
    - Accuracy of VTT solution is limited by small domain size (in horizontal direction) and by inaccurate predictions of HRR

Conclusions

- **Experimental data**
  - Database limited to near-field (*i.e.*, low elevations, $0 \leq z \leq D$)
    - Need a more complete description of the flame region ($0 \leq z \leq L_f$)
  - Flame is only weakly turbulent
    - Need larger flame sizes (*i.e.*, larger pool diameters)
  - The puffing instability is not fully characterized
    - Need information on time-dependent flame shape and/or an estimate of the amplitude of the puffing oscillations (both in the horizontal and vertical directions)
  - Thermal feedback is not characterized
    - Need measurements of the (convective/radiative) heat flux at the liquid fuel surface