Prototype HR2 Heat Release Apparatus Under Development

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HR2 Heat Transfer Model

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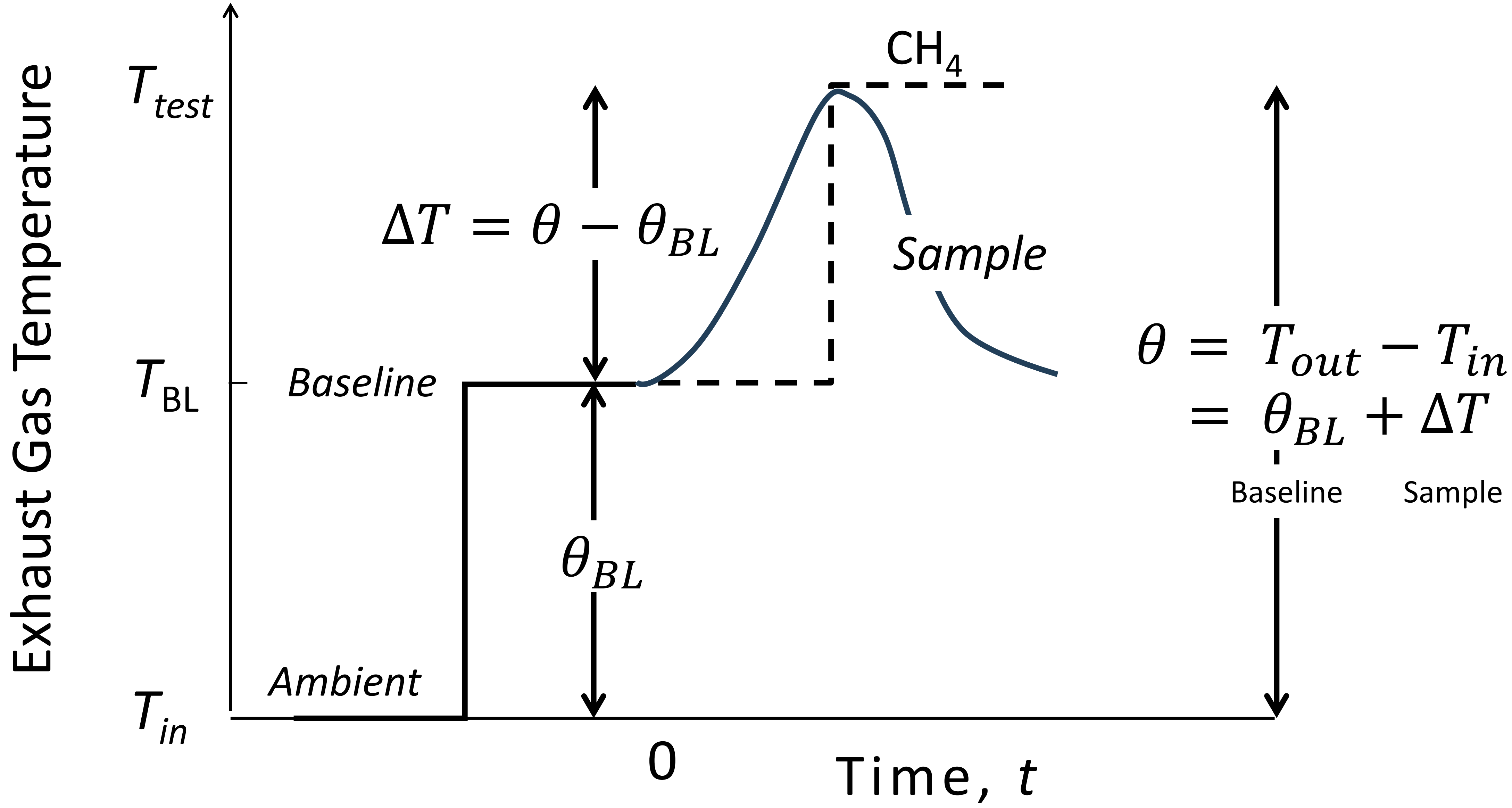
Temperature Histories in HR2



HR2 Standard Operation According to the Fire Test Handbook

Calibration Factor (Static)

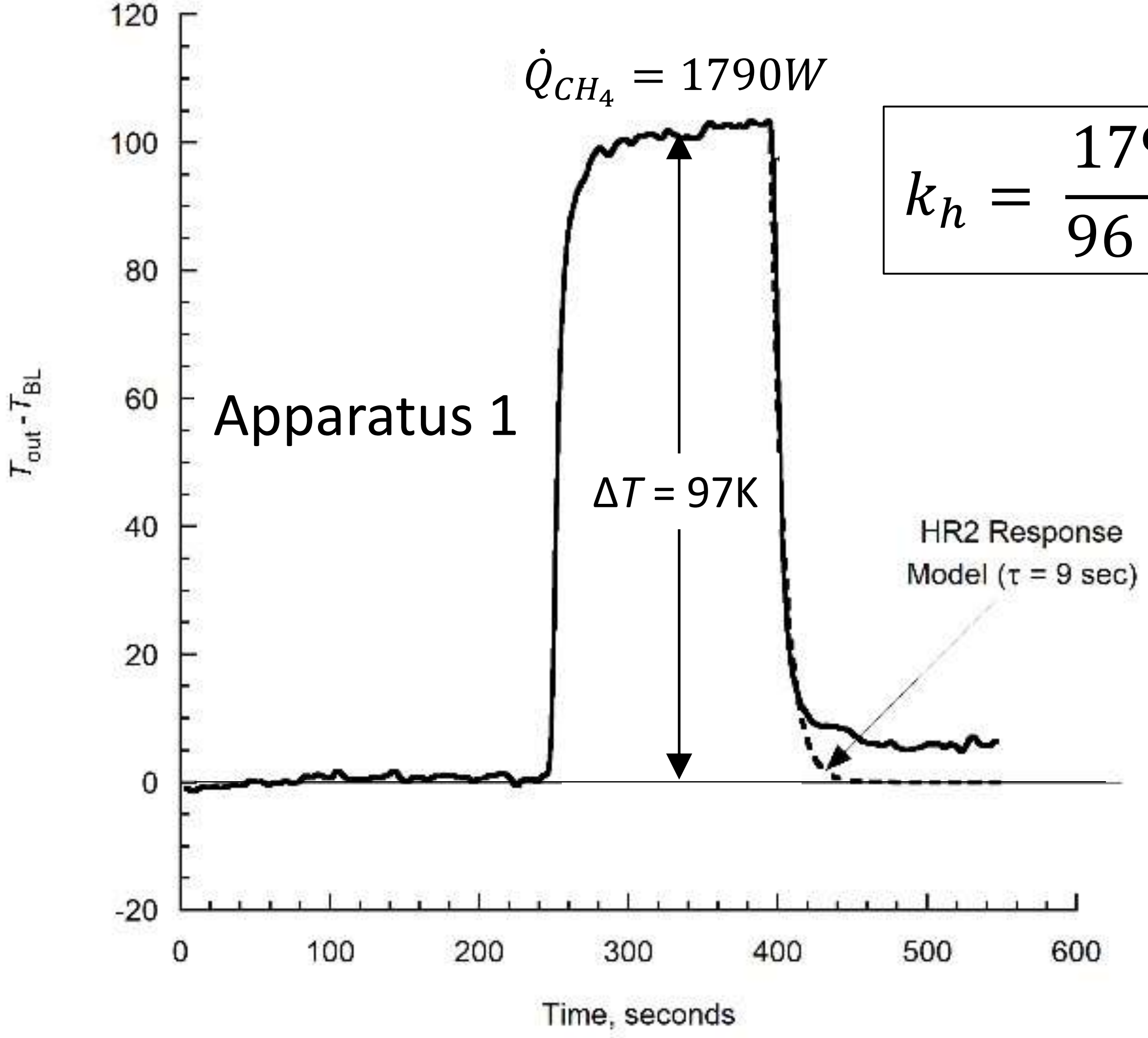
$$k_h = \frac{\dot{Q}_{CH_4}}{\Delta T_{CH_4}} = \frac{\left(H_c \rho \dot{V}\right)_{CH_4}}{\Delta T_{CH_4}} \approx 20\,\frac{W}{K}$$

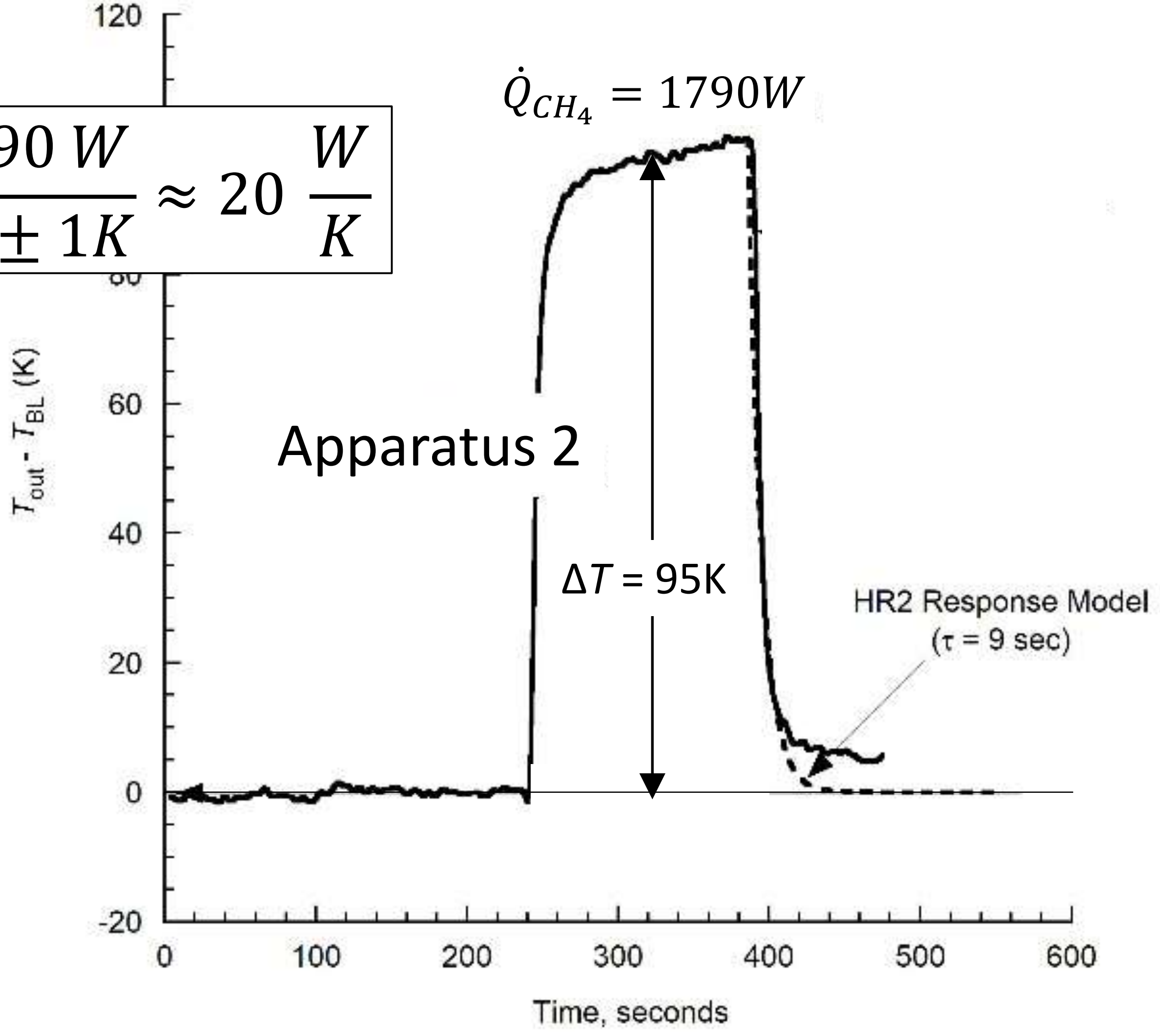
Heat Release Rate (Static Calibration)

$$\mathrm{HRR}\left(\frac{W}{m^2}\right) = \frac{Combustion\ Rate}{Sample\ Area} = \frac{\dot{Q}(t)}{A} = k_h \frac{\Delta T(t)}{A}$$

Methane Calibration

$$k_h = \frac{1790\,W}{96 \pm 1K} \approx 20\ \frac{W}{K}$$





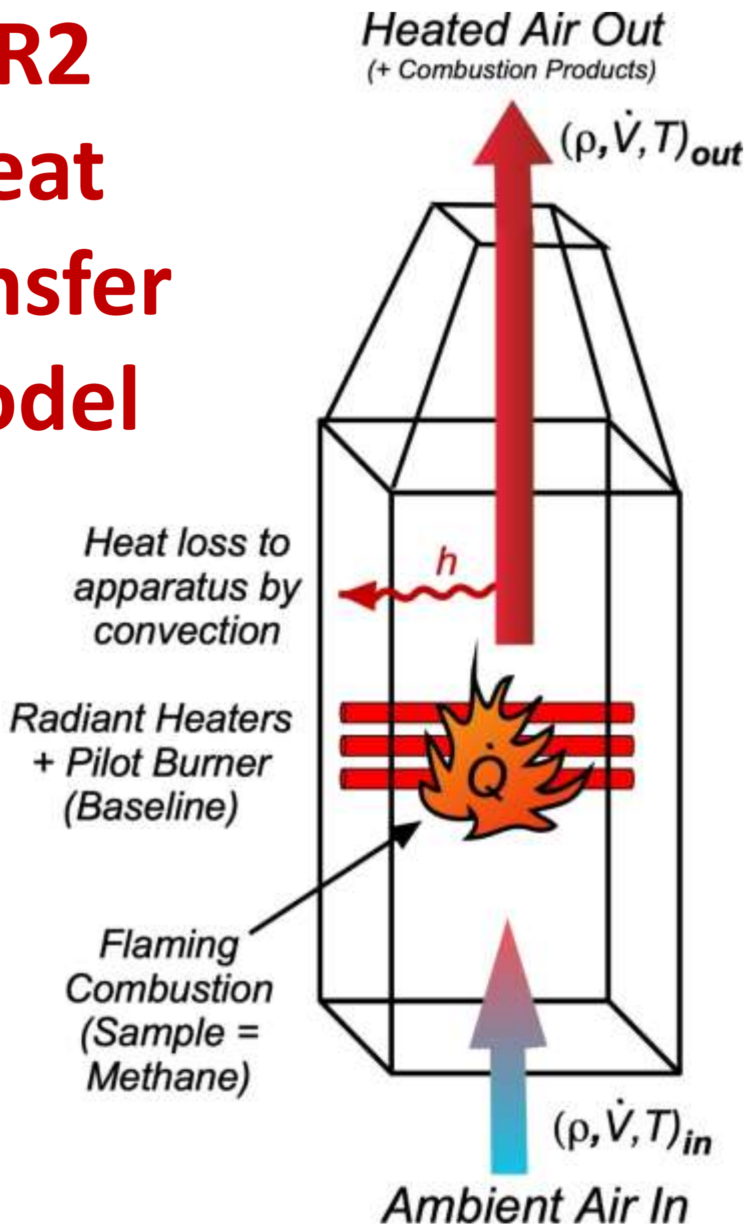
Problem Statement

The standard procedure with static methane calibration doesn’t tell us anything about how the dynamics of the HR2 affect the HRR results

Potential Solution

Develop and validate a heat transfer model for the HR2

HR2 Heat Transfer Model



Mass Balance

$$(\rho\dot{V})_{out} = (\rho\dot{V})_{in}$$

Energy Balance ($\theta = T_{out} - T_{in}$)

Sample heat Release rate

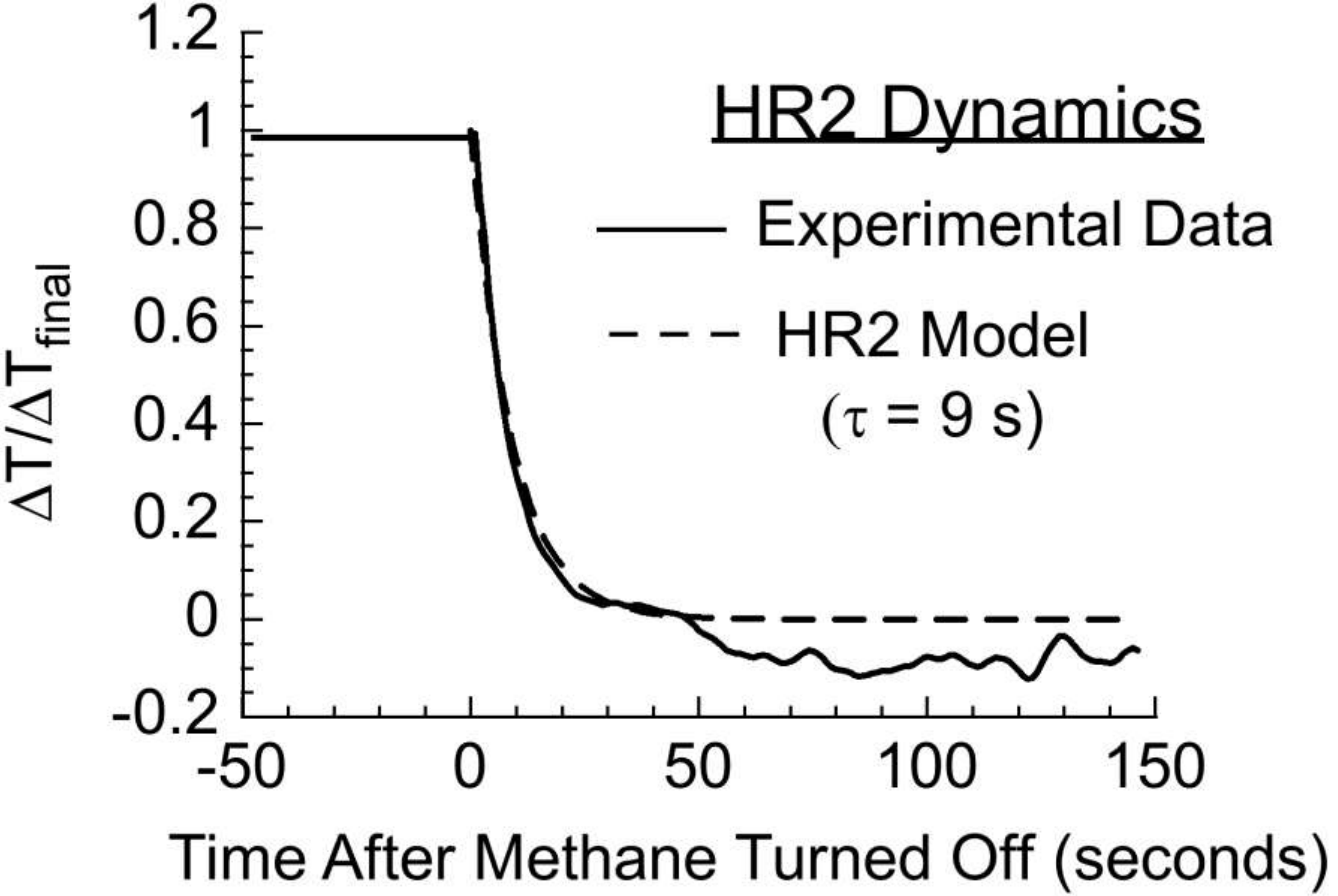
$$\frac{d}{dt}(mc_P\theta)_{air} = mc_P\frac{d\theta}{dt} + \rho c_P\dot{V}\theta = \dot{Q} - hS\theta$$

Thermal Energy Dynamics

Heat losses by convection

$$\frac{d\theta}{dt} + \frac{\theta}{\tau} = \frac{\dot{Q}}{mc_P}$$

Governing Equation HR2 Dynamics


HR2 Dynamics
Experimental Data
HR2 Model
(τ = 9 s)
ΔT/ΔT final
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-50
0
50
100
150
Time After Methane Turned Off (seconds)

Energy Balance Allows for Automatic (In Situ) Calibration

HR2 Automatic Calibration Factor

$$k_{auto} \equiv \frac{\dot{Q}_{BL}+\dot{Q}_{sample}(t)}{\theta_{BL}+\Delta T_{sample}} = \frac{\dot{Q}_{BL}+\dot{Q}_{sample}(t)}{\theta(t)}$$

Baseline Combustion Rate

$$\dot{Q}_{BL} = \left(\rho c_P \dot{V} + hS\right)_{air}$$

Standard Combustion Rate
(Methane Equivalent)

$$\dot{Q}_{test} = \left\{\frac{\left(\rho H_c \dot{V}\right)_{CH_4}}{\Delta T_{CH_4}}\right\} \Delta T(t) = k_h \Delta T(t)$$

Static Calibration Factor

Heat Release Rate (Dynamic Calibration)

$$\mathrm{HRR}\left(\frac{W}{m^2}\right) = \frac{\dot{Q}(t)}{A} = \left\{\frac{\dot{Q}_{BL}}{\theta} + \frac{\dot{Q}_{sample}}{\theta}\right\}\frac{\Delta T(t)}{A}$$

$$= \left\{\frac{\left(\rho c_P \dot{V} + hS\right)_{air} + k_h \Delta T(t)}{\theta(t)}\right\}\frac{\Delta T(t)}{A}$$

$$= \left\{\frac{c_1 + c_2 \Delta T(t)}{\theta(t)}\right\}\frac{\Delta T(t)}{A}$$

$\longleftarrow k_{auto} \longrightarrow$

Constants

Measured

Baseline (BL) has all info needed for Dynamic Calibration

$$\theta_{BL} = T_{BL} - T_{in} = \frac{1}{k_{BL}} \left(\dot{Q}_{\underset{(6000W)}{glowbars}} + \dot{Q}_{\underset{(900W)}{pilot}} \right) = \frac{\dot{Q}_{BL}}{k_{BL}}$$

From static energy balances,

$$k_{BL} = \frac{\dot{Q}_{BL}}{\theta_{BL}} = \frac{6900W}{613K - 295K} = \left(\rho \dot{V} c_P + hS \right)_{air} = 20\ \frac{W}{K} = k_h$$

Calibration constant is independent of energy source,

$$k_{auto} = \left(\frac{c_1 + c_2 \Delta T(t)}{\theta(t)} \right)_{c_2 = k_{BL}} = k_h$$

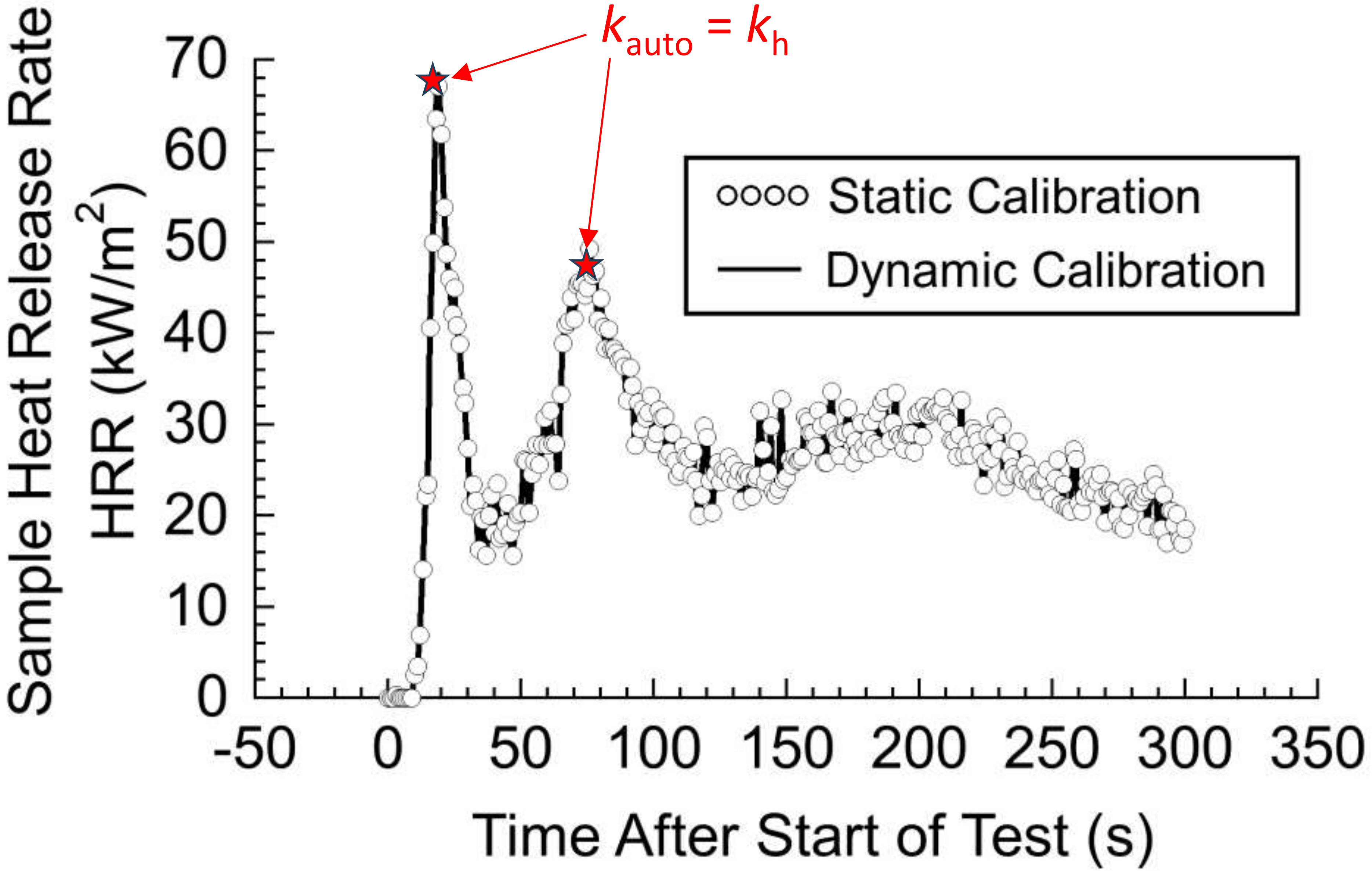
k_{auto} = k_h <u>only</u> at Maximum Heat Release Rate (HRR_{max})

$$\frac{d}{dt}\left(\frac{d\theta}{dt}+\frac{\theta}{\tau}=\frac{\dot{Q}}{mc_P}\right)=\underbrace{\ddot{\theta}}_{0}+\frac{\dot{\theta}}{\tau}=\underbrace{\frac{\ddot{Q}}{mc_P}}_{0}=0$$

$$\frac{\dot{\theta}}{\tau}=\frac{1}{\tau}\frac{d\theta}{dt}=\frac{1}{\tau}\frac{d\Delta T}{dt}=0$$

Only at $\dot{\boldsymbol{Q}}_{\boldsymbol{max}}$

$$\Delta T=Constant=\frac{\dot{Q}_{max}}{k_{auto}}=\frac{\dot{Q}_{CH_4}}{k_h}\quad\Rightarrow\quad\frac{\dot{Q}_{max}}{\dot{Q}_{CH_4}}=\frac{k_{auto}}{k_h}=1$$



$k_{auto} = k_h$
Sample Heat Release Rate
HRR (kW/m^2)
70
60
50
40
30
20
10
0
-50
0
50
100
150
200
250
300
350
Time After Start of Test (s)
Static Calibration
Dynamic Calibration

Conclusions

Position of heat sources (glowbars, pilots, sample) and sinks (sample fixture) in HR2 determine how much heat will be lost to apparatus and the value of k_{auto} and k_{h} used to measure HRR.

$$\text{HRR}\left(\frac{kW}{m^2}\right) = \underbrace{\left\{\frac{\left(\rho c_P \dot{V} + hS\right)_{air} + k_h \Delta T(t)}{\theta(t)}\right\}}_{Dynamic\ Calibration\ Factor} \frac{\Delta T(t)}{A}$$

$$k_{auto} = \left\{\frac{c_1 + c_2 \Delta T(t)}{\theta(t)}\right\}$$

Constants

Measured

$$c_1 = \left(\rho c_P \dot{V} + hS\right)_{air} = Heat\ transfer\ contribution\ to\ kauto$$