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ESTIMATION OF FINAL HYDROGEN TEMPERATURE FROM REFUELING PARAMETERS

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Introduction

- For safety reasons, the final gas temperature in the hydrogen tank during refueling is limited to 85℃. Many experiments have been done for determining the final gas temperature in the hydrogen tank.
- Lots of numerical simulations based on computational fluid dynamics have been performed and compared with experiments.
- The rule of mixtures is a general weighted average method, which has been widely used to estimate various properties of a composite materials, porous media and multiphase system.
- The effective (moderate) temperature of the mixture (cold and warm hydrogen, or hydrogen and tank wall, or even hydrogen and porous adsorbent) can be estimated based on the energy balance method.
- We will apply the conception and the method to study effect of initial and final mass, effect of inlet and initial temperatures, effect of initial pressure and average pressure ramp rate (APRR), effect of initial pressure, ambient temperature and mass flow rate. The fittings agree very well with the original data.

Equations of Lumped Parameter Model

THERMODYNAMIC MODEL

- **Mass balance equation**

$$\frac{dm}{dt} = \dot{m} \quad \text{where} \quad \dot{m} = \dot{m}_{\text{in}} - \dot{m}_{\text{out}}$$

- **Energy balance equation**

$$m = m_0 + \dot{m}t$$

$$\frac{d}{dt}(mu) = \dot{m}h + \dot{Q} \quad \text{where} \quad \dot{m}h = \dot{m}_{\text{in}}h_{\text{in}} - \dot{m}_{\text{out}}h_{\text{out}}$$

$$m = m_0 + \dot{m}t$$

$$(m_0 + \dot{m}t)\frac{du}{dt} + \dot{m}u = \dot{m}h + \dot{Q} \quad \text{where} \quad \dot{Q} = a_f A_s (T_f - T)$$

$$t^* = m_0 / \dot{m} \qquad q = \dot{Q} / \dot{m}$$

$$(t^* + t)\frac{du}{dt} + u = h + q$$

Analytical Solution of Energy Equation

THERMODYNAMIC MODEL

$$\left(t^* + t\right)\frac{du}{dt} + u = h + q \quad \text{where} \quad u = c_v T$$

$$h = c_p T_\infty$$

$$q = c_v \alpha \left(T_f - T\right)$$

↓

$$\frac{dT}{dt} = \left(1 + \alpha\right)\frac{T^* - T}{t^* + t} \quad \text{where} \quad T^* = \frac{\gamma T_\infty + \alpha T_f}{1 + \alpha}$$

$$\alpha = a_f A_s / \left(c_v \dot{m}\right)$$

$$\gamma = c_p / c_v$$

↓

$$\frac{T^* - T}{T^* - T_0} = \left(\frac{1}{1 + \tau}\right)^{1+\alpha} \quad \text{where} \quad \tau = t / t^*$$

THERMODYNAMIC MODEL

Weighted Averaging Form of Temperature

- Solutions of mass and energy equations

$$m = m_0 + \dot{m}t \quad \Rightarrow \quad m/m_0 = 1 + \tau$$

$$t^* = m_0 / \dot{m}, \quad \tau = t / t^*$$

$$\frac{T^* - T}{T^* - T_0} = \left(\frac{1}{1+\tau} \right)^{1+\alpha} \quad \Rightarrow \quad \frac{T^* - T}{T^* - T_0} = \mu'$$

$$\mu = m_0 / m, \quad \mu' = \mu^{1+\alpha}$$

- Weighted averaging form of temperature

$$T = \mu' T_0 + (1 - \mu') T^* \qquad \text{(Rule of mixture)}$$

Analogy for Finial Gas Temperature

THERMODYNAMIC MODEL

- Adiabatic tank not considering thermal capacity of the wall

$$mc_vT = m_0c_vT_0 + (m - m_0)c_pT_\infty$$

$$T = \mu T_0 + (1 - \mu)T^* \quad \text{where} \quad T^* = \gamma T_\infty$$

- Adiabatic tank considering thermal capacity of the wall

$$mc_vT + m_wc_wT_w = m_0c_vT_0 + m_wc_wT_{w0} + (m - m_0)c_pT_\infty$$

If the conductive resistance of the tank wall is neglectable, the wall temperatures equal to the hydrogen temperatures, i.e.

$$T_w = T \qquad T_{w0} = T_0$$

So $$T = f_{\mathrm{MC}}T_0 + (1 - f_{\mathrm{MC}})T^* \quad \text{(Rule of mixture)}$$

where $$f_{\mathrm{MC}} = (m_0c_v + m_wc_w)/(mc_v + m_wc_w)$$

Final / Initial Mass Ratio - Model

RESULTS AND DISCCUSIONS

$$T = \mu' T_0 + (1-\mu')T^*$$

$$\frac{T}{T_0} = \mu' + (1-\mu')\frac{T^*}{T_0}$$

$$\frac{T}{T_0} = \frac{T^*}{T_0} - \left(\frac{T^*}{T_0} - 1\right)\mu'$$

$$\mu' = \mu^{1+\alpha} = \left(\frac{m_0}{m}\right)^{1+\alpha} \qquad A = T^* / T_0 \qquad C = 1+\alpha$$

$$\frac{T}{T_0} = A - (A-1)\left(\frac{m}{m_0}\right)^{-C}$$

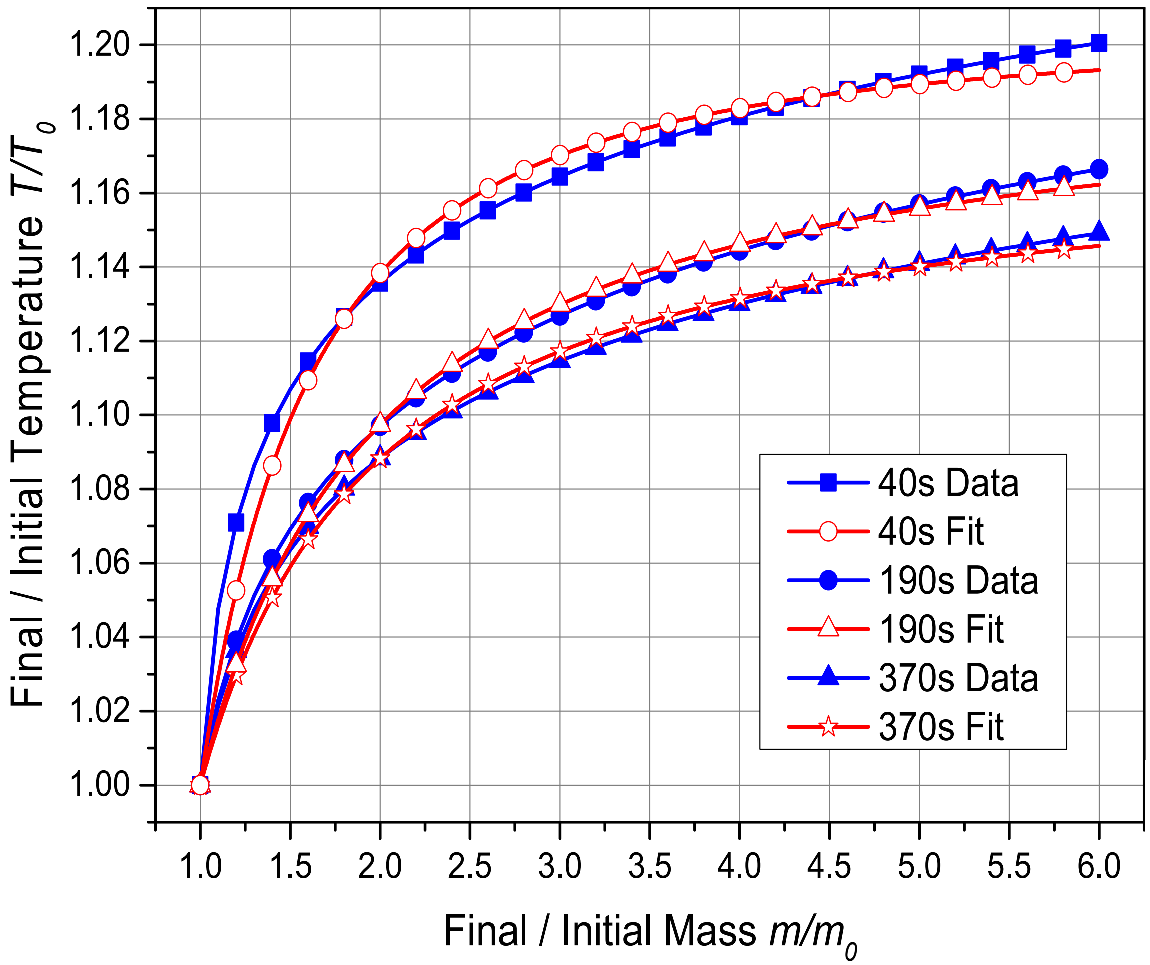
Two-parameter formula

$$\frac{T_{mean}}{T_i} = \left(A + B\left(\frac{m}{m_i}\right)^{1/2}\right)^C$$

Three-parameter formula

W. Merida. JPS 165 (2007) :324-336

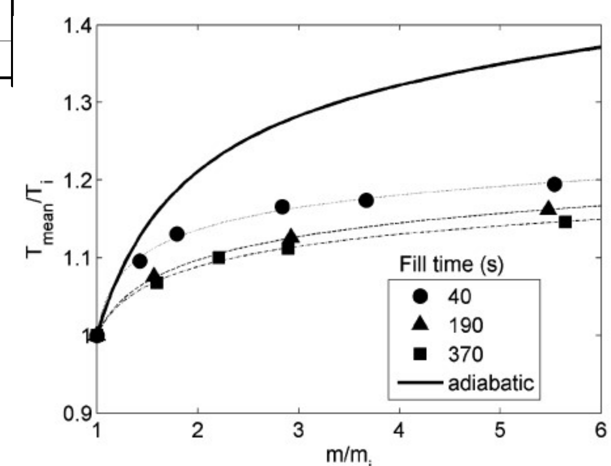
Final / Initial Mass Ratio - Results



$$\frac{T}{T_0} = A - (A-1)\left(\frac{m}{m_0}\right)^{-C}$$

The derived two-parameter formula has same ability to represent experimental data with the three-parameter formula.

$$\frac{T_{mean}}{T_i} = (A + B(\frac{m}{m_i})^{1/2})^C$$



W. Merida. JPS 165(2007):324-336

Inlet and Initial Temperatures - Model

$$T = \mu' T_0 + (1 - \mu') T^*$$

$$T^* = \frac{\gamma T_\infty + \alpha T_f}{1 + \alpha}$$

$$T = \mu' T_0 + \frac{1 - \mu'}{1 + \alpha} \gamma T_\infty + \frac{1 - \mu'}{1 + \alpha} \alpha T_f$$

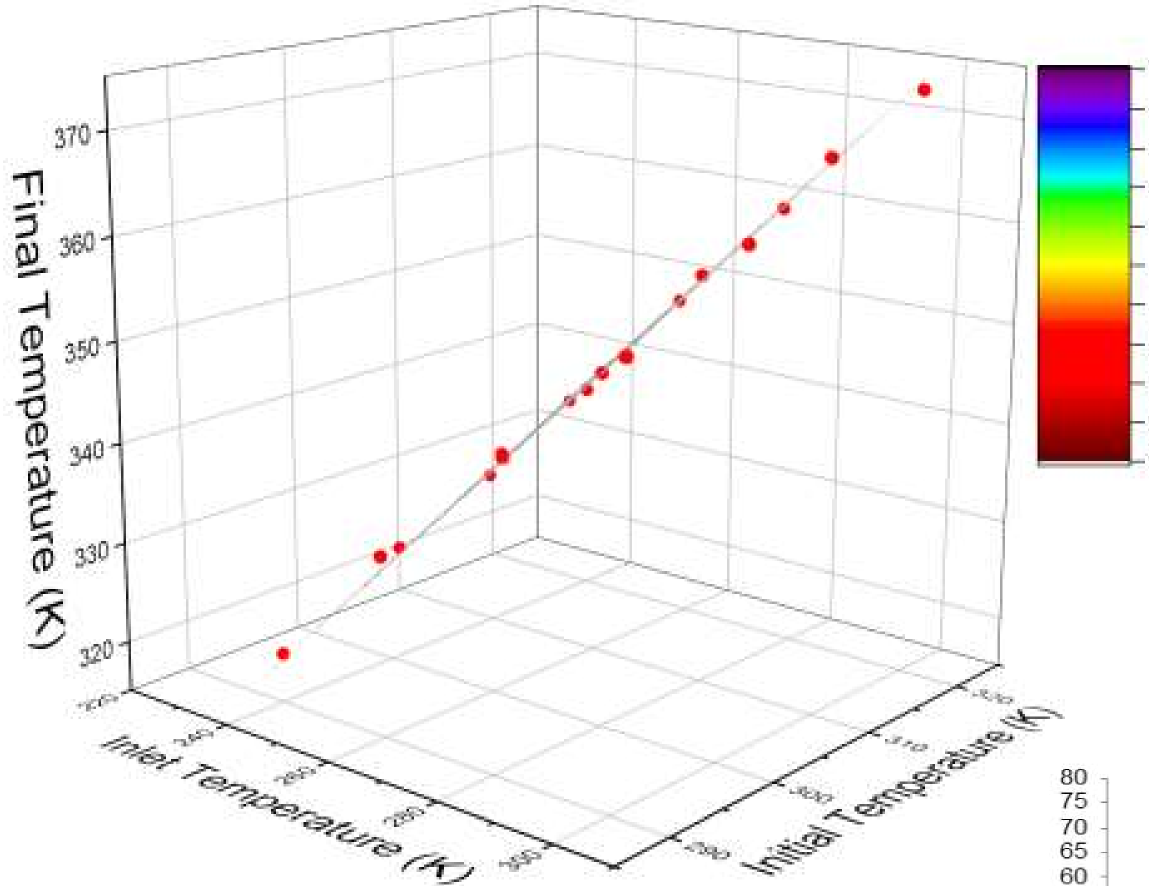
$$\alpha = 0$$

$$T = \mu T_0 + (1 - \mu) \gamma T_\infty$$

Function of inlet and initial temperatures

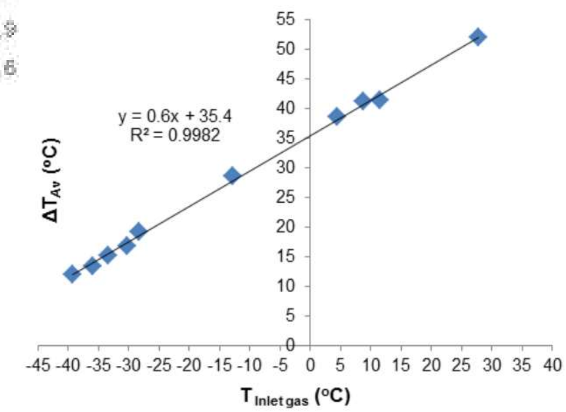
Inlet and Initial Temperatures - Results

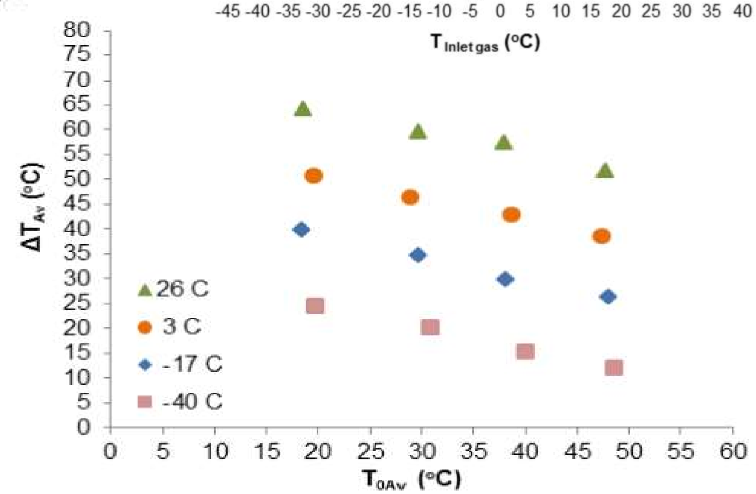
RESULTS AND DISCCUSIONS



B. Acosta.
WHEC2014
Paper 1848

y = 0.6x + 35.4
$R^2 = 0.9982$





$$T = 0.59853T_0 + 0.60736T_\infty$$

Fitted parameter 0.60736 agrees with the number of 0.6 from linear curve fitting.

Initial Pressure and APRR - Model

RESULTS AND DISCCUSIONS

$$T = \mu' T_0 + (1 - \mu') T^*$$

$$T_\infty = T_f$$

$$T^* = \frac{\gamma T_\infty + \alpha T_f}{1 + \alpha} = \frac{\gamma + \alpha}{1 + \alpha} T_f$$

$$T = \mu' T_0 + (1 - \mu') \frac{\gamma + \alpha}{1 + \alpha} T_f$$

$$\alpha = (a_f A_s)/(c_v \dot{m})$$

$$\alpha = B / \dot{p} = B / \mathrm{APRR}$$

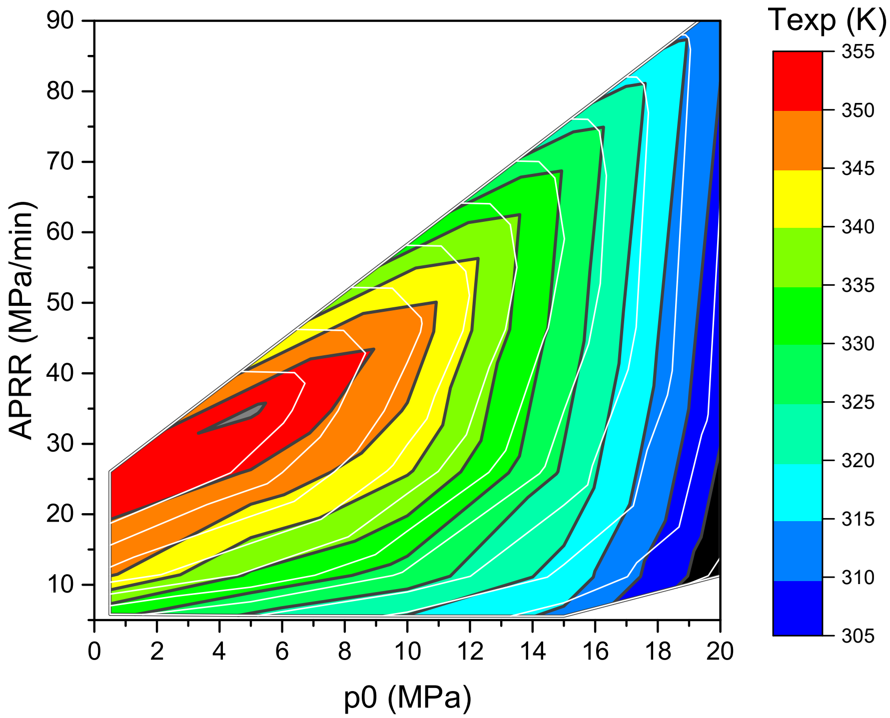
$$\mu' \approx \mu = A p_0$$

$$T = A p_0 T_0 + (1 - A p_0) \frac{\gamma + B / \dot{p}}{1 + B / \dot{p}} T_f$$

Function of initial pressure and APRR

Initial Pressure and APRR - Results

RESULTS AND DISCCUSIONS

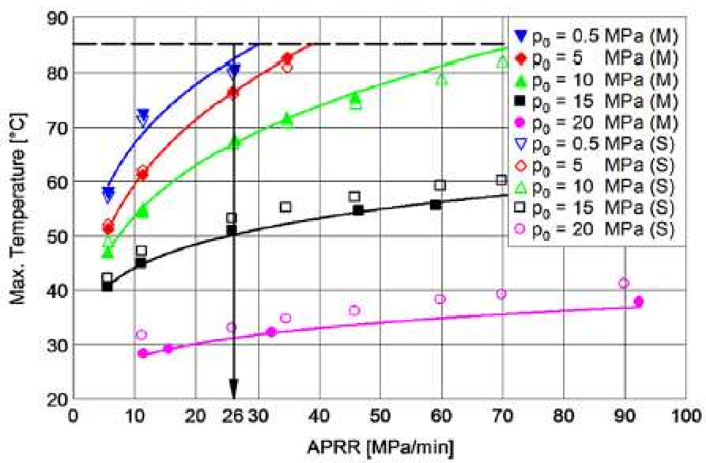


$$T_\infty = T_f = T_0 = 293.15K \quad \gamma = 1.4$$

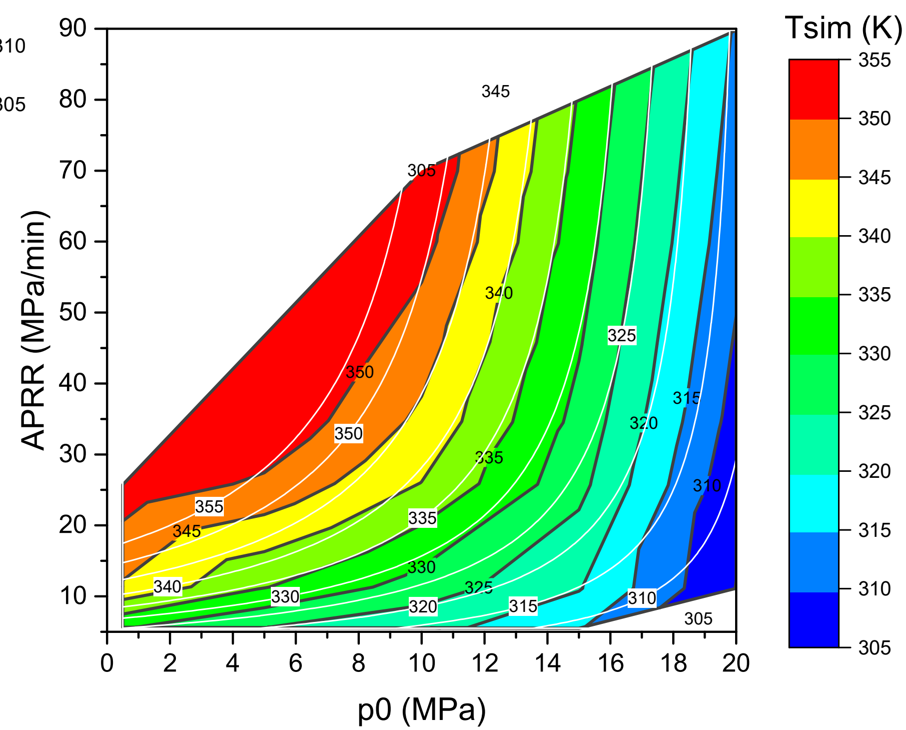
White curves: Fit

Black curves: Data

The fitting based on the simulated data is better than that based on the experimental data because it has more data points.



M. Klell. IJHE 39(2014): 8495-8509



RESULTS AND DISCCUSIONS

Initial P, Ambient T and MFR - Model

$$T = \mu' T_0 + (1-\mu')T^*$$

$$T_0 = 293.15\text{K}$$

$$\gamma = 1.4$$

$$\mu' = K_p p_0$$

$$\alpha = K_m / \dot{m}$$

$$T^* = \frac{\gamma T_\infty + \alpha T_f}{1+\alpha}$$

$$T = \mu' T_0 + \frac{1-\mu'}{1+\alpha}\gamma T_\infty + \frac{1-\mu'}{1+\alpha}\alpha T_f$$

$$T_\infty = T_0,\ T_f = T_0$$

$$T = \left(\frac{\gamma+\alpha}{1+\alpha} - \frac{\gamma-1}{1+\alpha}\mu'\right)T_0$$

Negatively linear with initial pressure

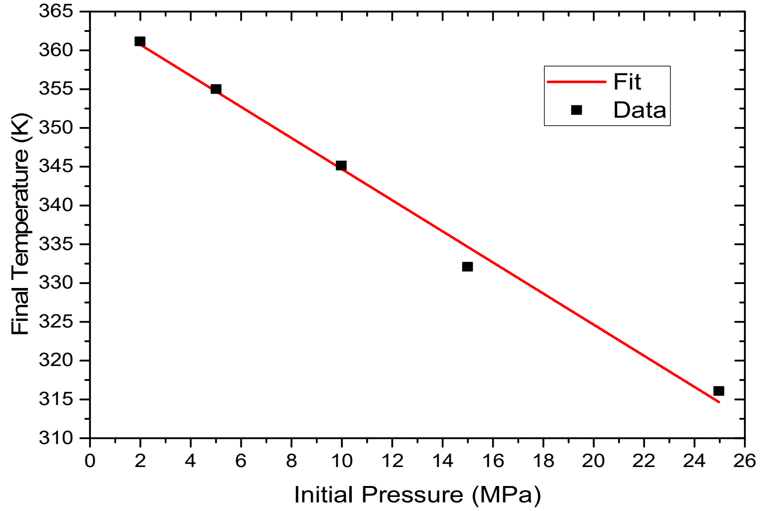
$$T_\infty = T_0$$

$$T = \left(\mu' + \frac{1-\mu'}{1+\alpha}\gamma\right)T_0 + \frac{1-\mu'}{1+\alpha}\alpha T_f$$

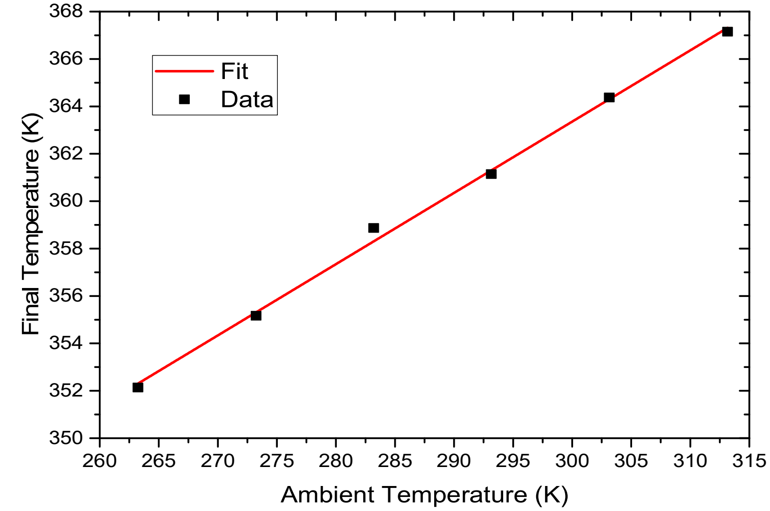
Positively linear with ambient temperature

Initial P, Ambient T and MFR - Results

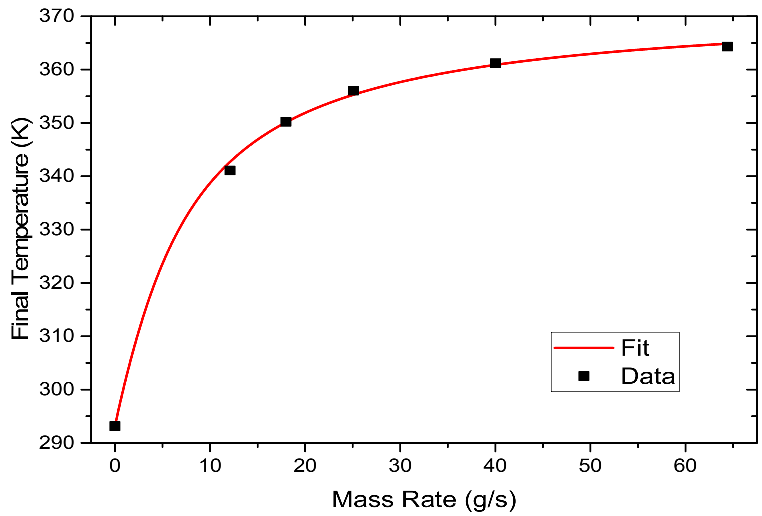
RESULTS AND DISCCUSIONS



(a)



(b)



(c)

Effects of (a) initial pressure, (b) ambient temperature, (c) hydrogen mass flow rate on final hydrogen temperature compared with data.

J.Y. Zheng. IJHE 35(2010): 8092-8100

Conclusion

- The energy, like density and heat capacity, is not sensitive with the structure of the mixture or composites. Therefore, the upper bound of the rule of mixtures is used to estimate the hydrogen temperature.
- The analytical solution of hydrogen temperature behaves in an analogous way as the rule of mixtures. The final hydrogen temperature is the weighted average of initial temperature and a characteristic temperature which is related the inflow enthalpy of hydrogen. The weighted factor is initial heat capacity fraction.
- The simple uniform formula, inspired by the concept of the rule of mixtures with its weighted factors obtained from the analytical solution of thermodynamic model, is applied to fit published experimental or simulated results.
- These results show effect of initial and final mass, effect of inlet and initial temperatures, effect of initial pressure and average pressure ramp rate (APRR), effect of initial pressure, ambient temperature and mass flow rate. The fittings agree very well with the original data.

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