Heat transfer from exothermically reacting fluid in vertical unstirred vessels

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Summary

Exothermically reacting fluid poses the danger of temperature run-away (thermal explosion) in some circumstance (e.g. interruption of stirring in a reactor and during storage). If the explosion time is longer than that required to establish free convection in a heat generating fluid, convection greatly modifies the internal temperature distributions relative to those developed when conduction operates. Experiments on free convection, using flow visualisation and temperature profiles, showed a thermally stratified core moving slowly upwards and a thin thermal boundary layer on the wall of an unstirred vertical cylindrical vessel. The highly exothermic isomerisation of trimethylphosphite was used as a test reaction. To avoid costly and dangerous experiments on the plant scale, an analogy between the temperature distributions in active (exothermically reacting) and passive (cooling without reaction) systems at equal heat removal rates was established and confirmed by experiments with the test mixture trimethylphosphite/methanephosphoric acid dimethyl ester.

The main results of the study are:

- The correlations found in the literature on heat transfer governed by natural convection (Nusselt/Rayleigh correlations) are valid for unstirred cylindrical reactors. The film heat transfer coefficients found are not even one order of magnitude smaller than for stirred systems.
  For turbulent natural convection (which occurs in large vessels at quite low temperature differences) the film coefficient is independent of vessel size and depends on physical properties of the fluid in the same manner as the forced convection film heat transfer coefficient.
- Because of stratification, the maximum average temperature difference between the bulk of the fluid and the wall, at which thermal run-away is avoided, is much smaller than in the stirred system (about 1/3).
- The maximum allowable specific heat release rate in the fluid is inversely proportional to the third root of the vessel volume, as for forced convection. This is in contrast to the situation where conduction prevails: there $q_c \sim V^{-2/3}$. Therefore, in large vessels, the maximum allowable specific heat release rate is much larger in fluids than in solids.

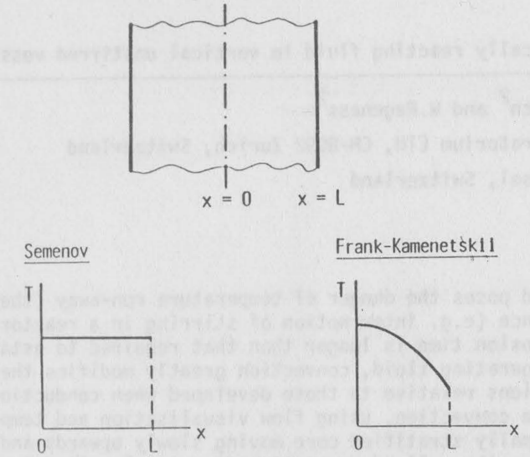


Fig. 1

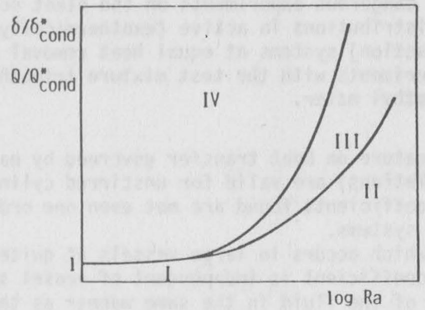


Fig. 2

Fig. 4

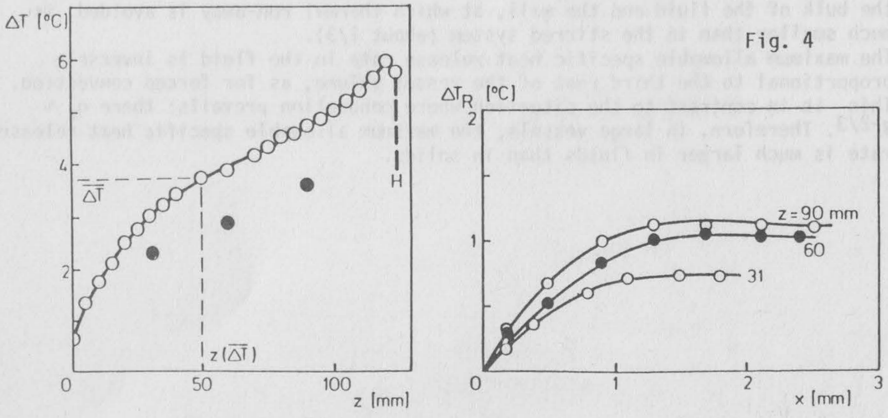
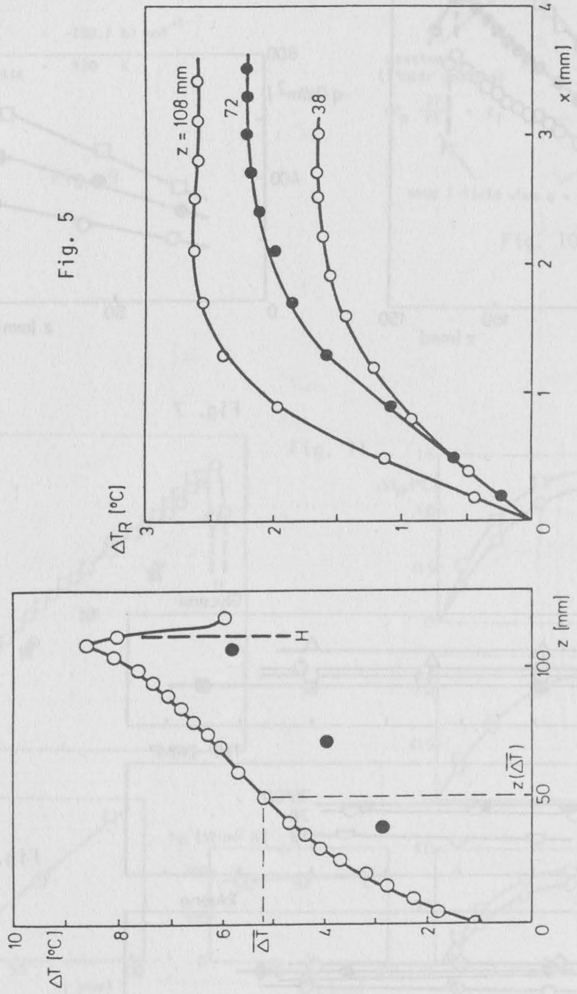


Fig. 5



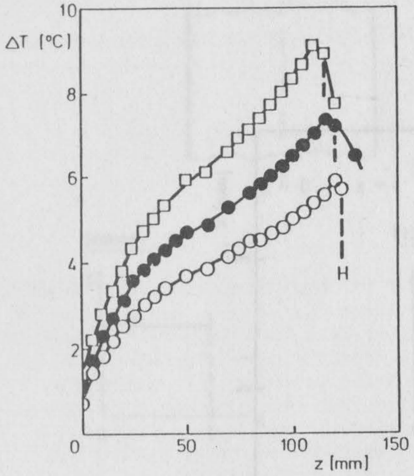


Fig. 6

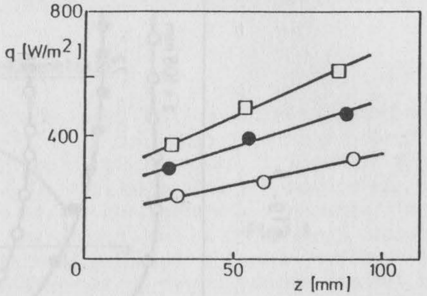


Fig. 7

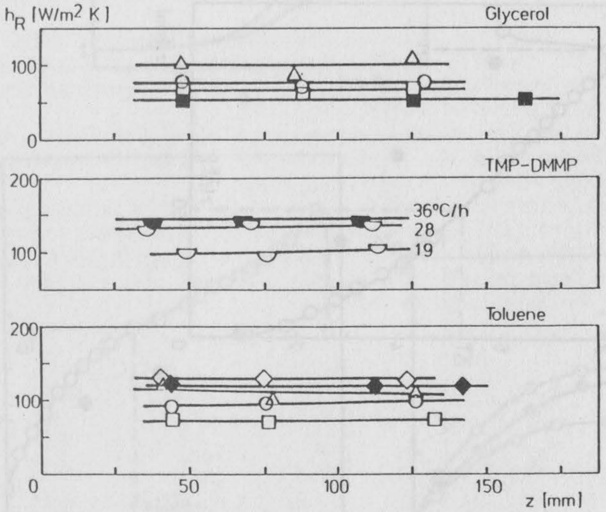
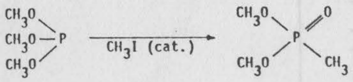


Fig. 8

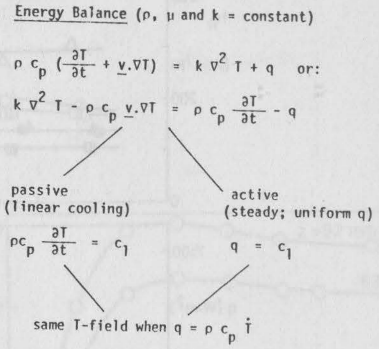
Isomerisation of Trimethyl Phosphite



Δh = -180.7 kJ mol^{-1}

$\Delta T_{adiabatic}$ = 570 K

Fig. 9



Energy Balance (ρ, μ and k = constant)

$$\rho\, c_p \left(\frac{\partial T}{\partial t} + \underline{v}.\nabla T\right) = k\, \nabla^2 T + q \quad \text{or:}$$

$$k\, \nabla^2 T - \rho\, c_p\, \underline{v}.\nabla T = \rho\, c_p \frac{\partial T}{\partial t} - q$$

passive (linear cooling)

$$\rho c_p \frac{\partial T}{\partial t} = c_1$$

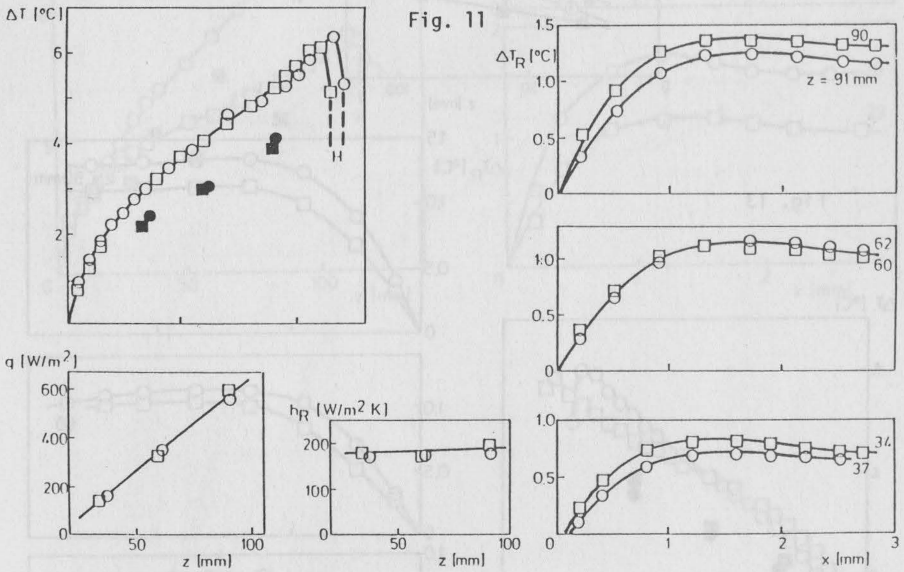
active (steady; uniform q)

$$q = c_1$$

same T-field when $q = \rho\, c_p\, \dot{T}$

Fig. 10

Fig. 11



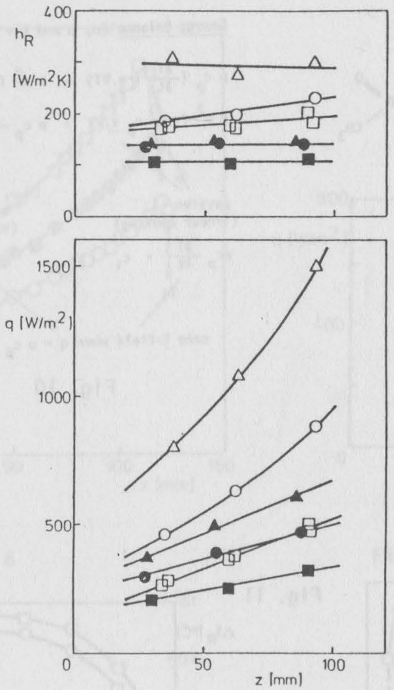


Fig. 12

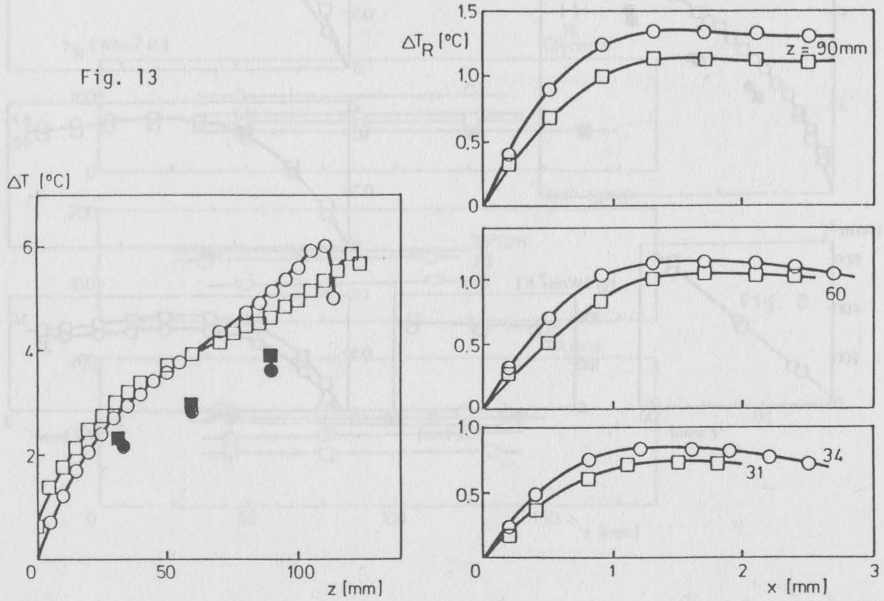


Fig. 13

Fig. 14

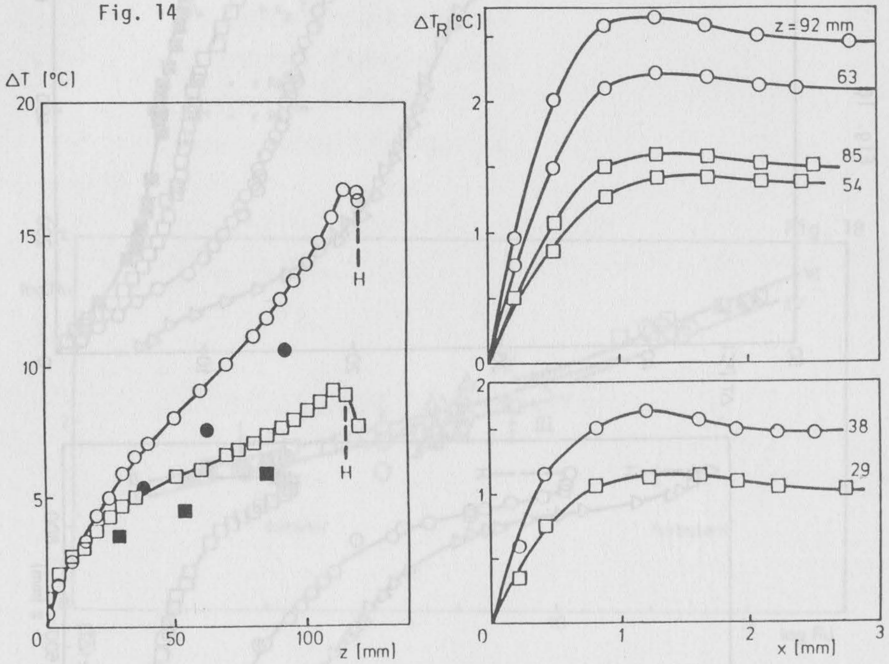


Fig. 16

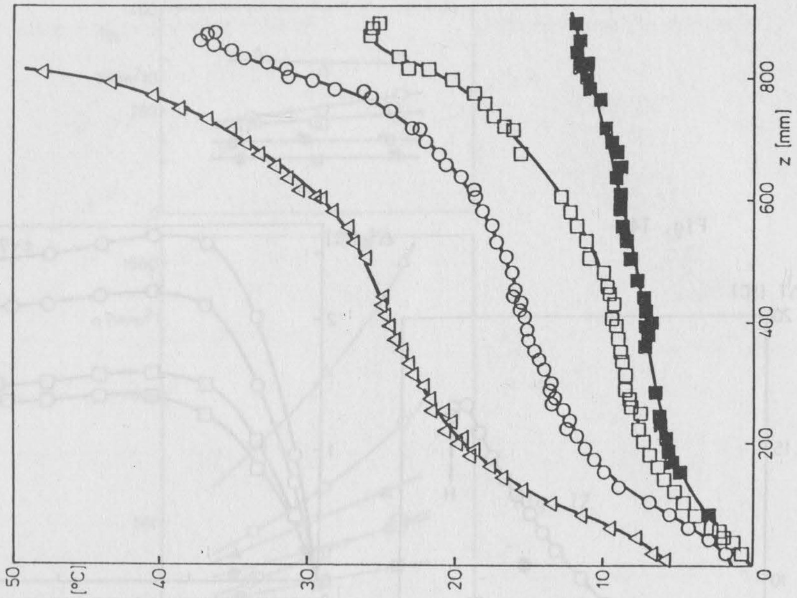
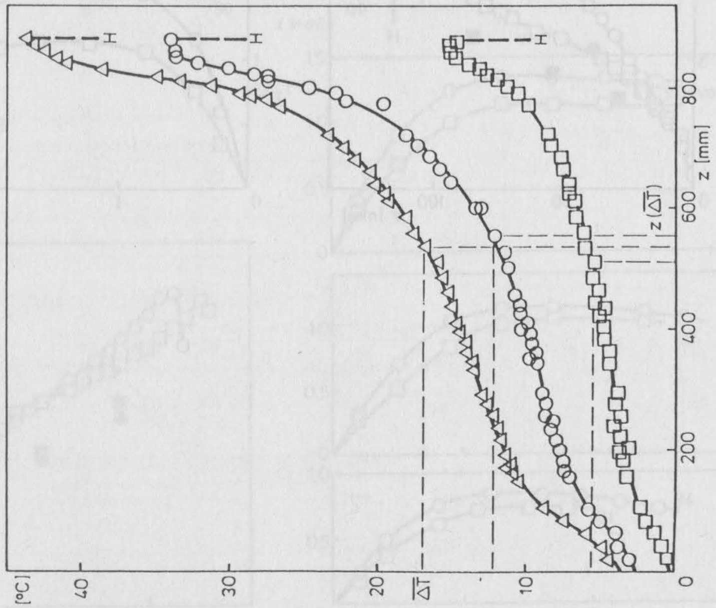


Fig. 15



Definitions

$$Ra = \frac{g\,\beta}{\alpha\,\nu} H^3 \overline{\Delta T}_R \qquad (1)$$

$$\overline{\Delta T}_R = u\,\overline{\Delta T}/h_R \;;\; \alpha = k/\rho c_p \;;\; \nu = \mu/\rho$$

Fig. 17

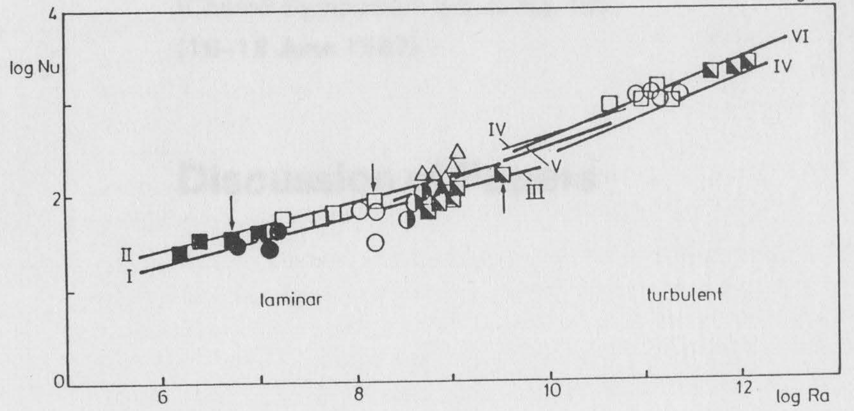
$$Ra^* = \frac{g\,\beta}{\alpha\,\nu} H^3 \frac{Q_p\,H}{k\,a} = \frac{g\,\beta}{\alpha\,\nu} H^3 \frac{\dot{T}\,H}{\alpha\,a} \qquad (2)$$

$$Q_p = \rho\, c_p\, \dot{T}$$

$$Nu = c\, Ra^m$$

$$Ra^* = c\, Ra^{1+m}$$

Fig. 18



Results

Laminar free convection: $Nu = 0.46\, Ra^{*0.22}$

$\sim Ra^{0.28}$

Fig. 19

Turbulent free convection: $Nu = 0.24\, Ra^{*0.26}$

$\sim Ra^{0.35}$

$\Delta T_{max} < RT_o^2/E$ $\quad$ $\Delta T_{max} \simeq 3\,\overline{\Delta T}$

$\tau_c \ll \tau_{ex}$