NATURAL CIRCULATION THROUGH SINGLE-ENDED EVACUATED TUBE SOLAR COLLECTORS

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Evacuated tube solar collectors

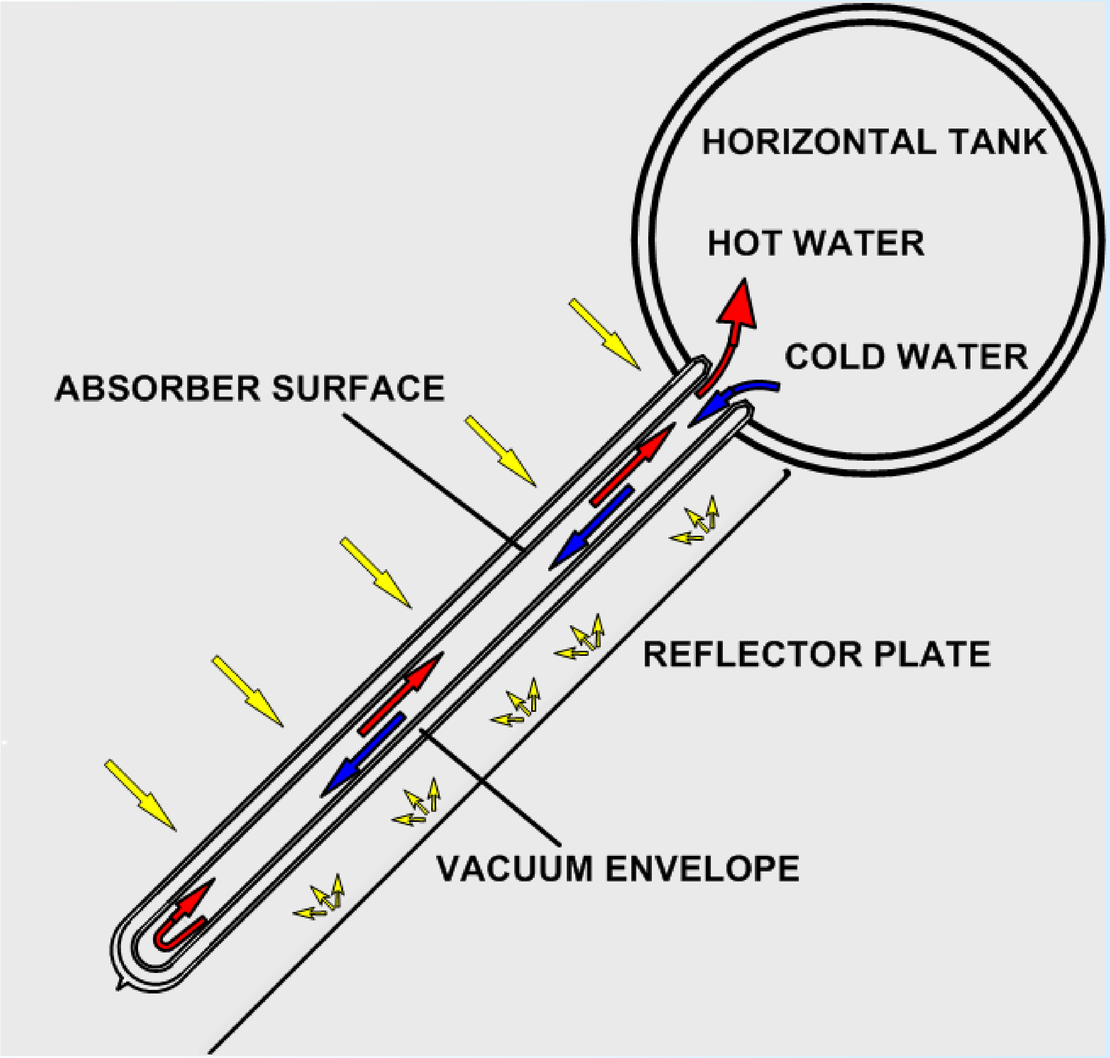
- Reduced convection heat loss compared to flat-plate collectors
- In the past had small market compared to flat-plate collectors
  1. Complex metal heat extraction manifolds
  2. Expensive to manufacture
  3. Difficulties to seal metal-to-glass joints
- 1980’s – low cost sputter coater (University of Sydney)
- Water-in-glass evacuated tubes with direct connection to a horizontal tank - 65% of 6.5 million m^2 per year in China
- Production capacity: 60 million tubes per year in 2003 (China)

Evacuated tube solar water heaters in China

Water-in-Glass Solar Water Heater

- 21 single-ended evacuated tubes with direct connection to a horizontal tank mounted over a diffuse reflector plate
- Collector inclination: 45º
- Tube aspect ratio (length/diameter): 1420/34
- Absorber diameter: 37 mm
- Inter-tube spacing: 70 mm

Heat transfer and fluid flow in single-ended evacuated tube solar collector



Performance Evaluation

Modelling of the system requires data on

- Heat loss of the storage tank
- Optical efficiency of the collector
- Heat loss of the evacuated tubes and efficiency equation
- Natural circulation flow rate through the tubes

Circulation flow rate through single ended evacuated tubes

- Collector flow rate determines the degree of mixing in the storage tank, in particular for systems adopting ‘direct’ circulation

- Thermal stratification in the storage tank influences solar water heater performance

High thermal stratification results in a higher fraction of tank volume that is available for domestic use (at delivery load temperature)

Lower temperature water at tank bottom circulates through the collector – higher efficiency

Factors influencing circulation rate

- Solar input
- Tank temperature – density gradient and viscosity of water varies significantly over collector operating temperatures
- Collector inclination – determines the components of gravity driven bouyancy in the axial direction (primary circulation) and radial direction (secondary circulation)
- Tube length-diameter ratio
- Circumferential solar flux distribution (reflector shape)

Methodology

Experimental

Outdoor temperature measurements

Numerical

Computational Fluid Dynamics (CFD) simulations

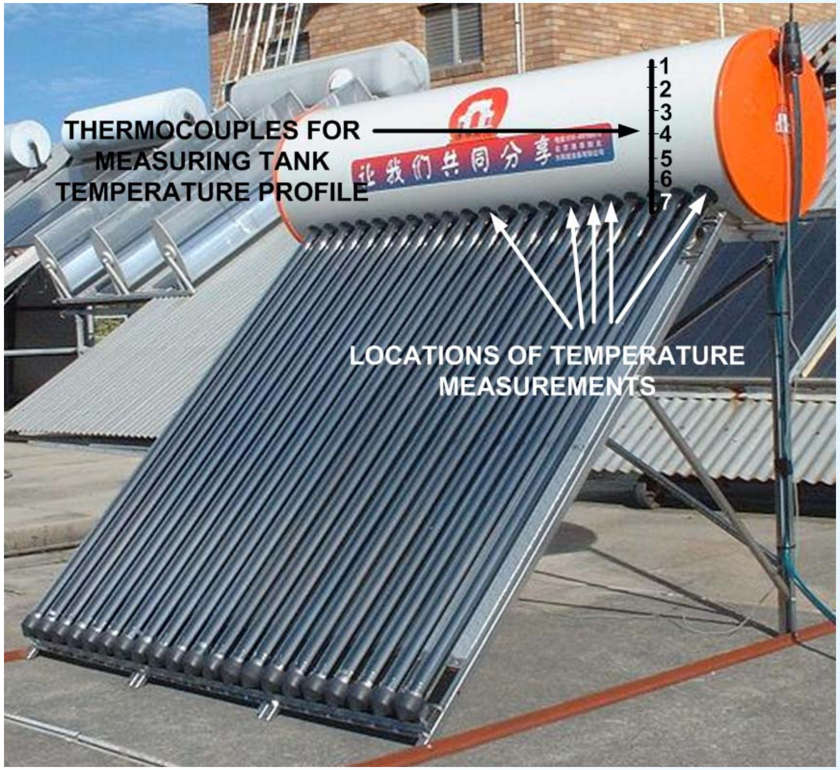
Indoor experimental program*

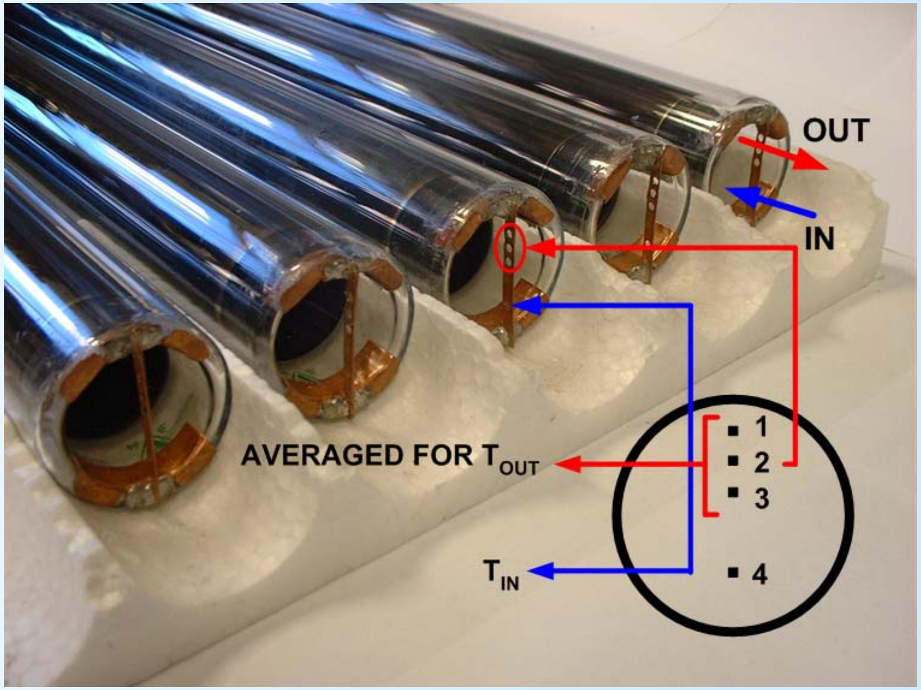
Single-ended tube with electric heating to simulate solar radiation

Particle Image Velocimetry (PIV) – measured detailed velocity profiles across tube opening

**presented at ISES Solar World Congress 2003 Gothenborg & Solar Energy V76,135*

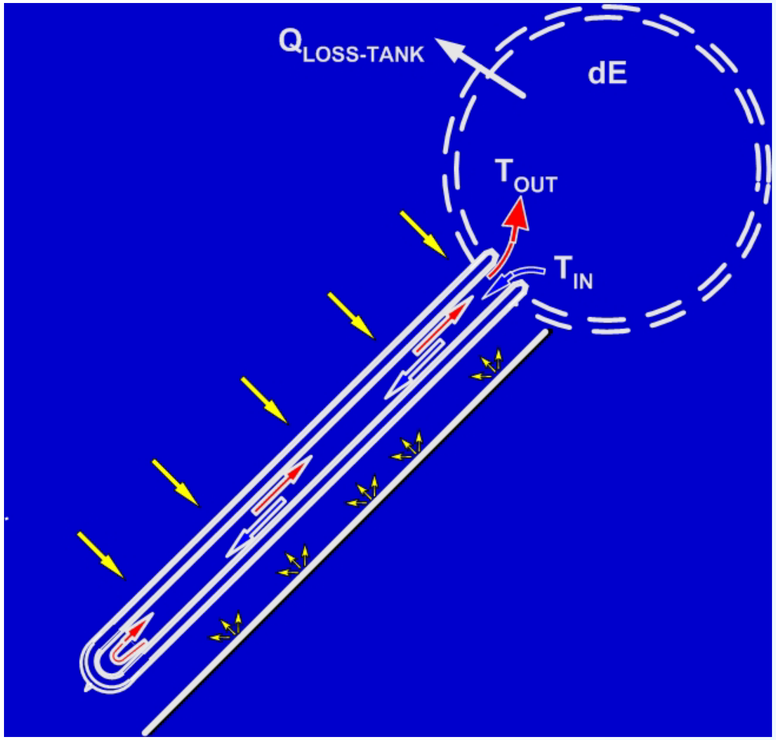
Direct temperature measurements to determine circulation flow rate





- ½-hr period across solar noon – radiation normal to collector
- Tank temperature measured at 7 levels
- In-flow and out-flow temperatures across opening of 5 tubes

Computation of circulation flow rate from temperature measurements



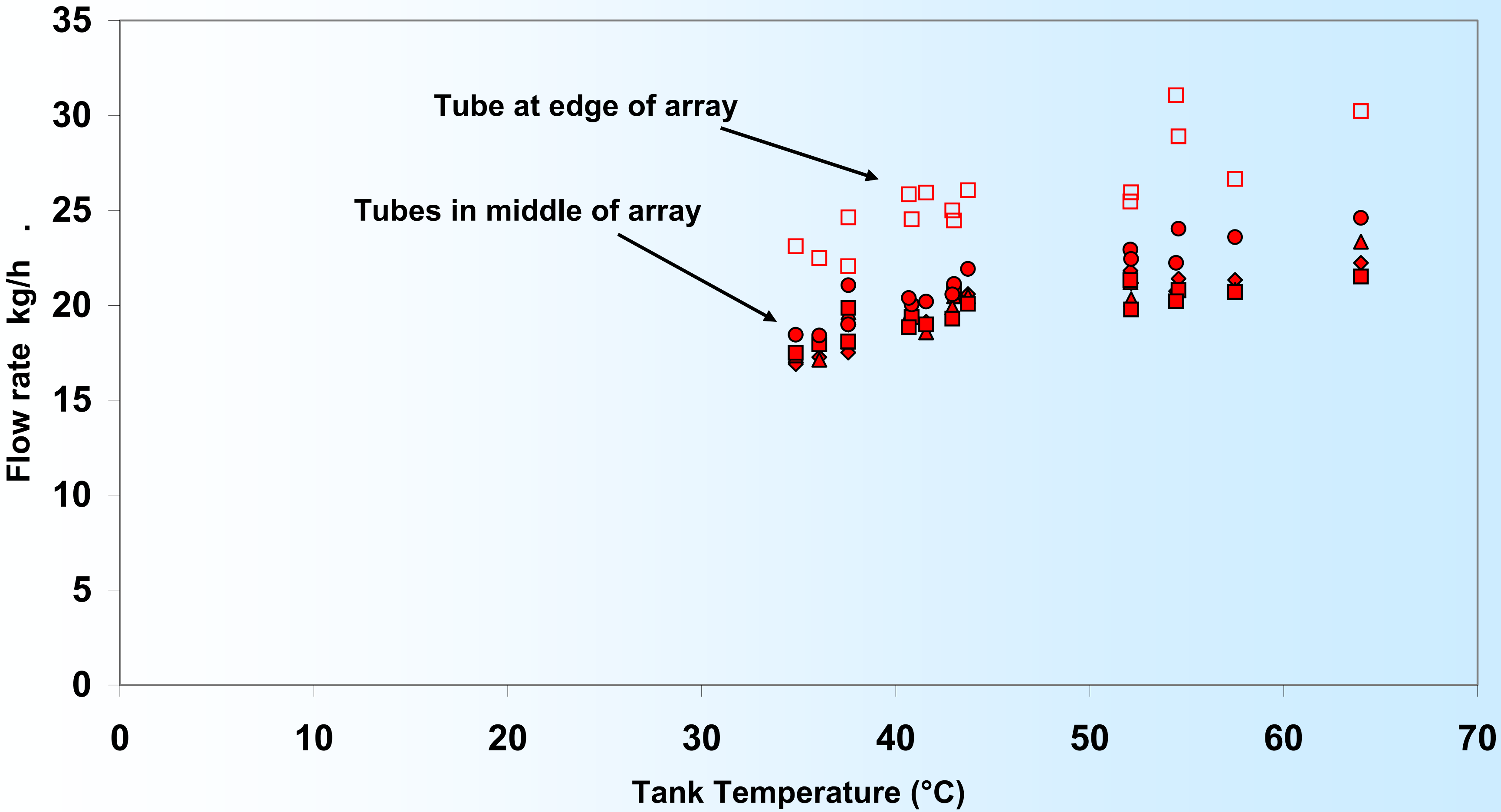
$$Q_{u-collector} = dE_{system} + Q_{loss-tank}$$

$$= mc_p(T_2 - T_1) + \int_{t_1}^{t_2} U_{loss-tank} A_{tank} (\overline{T} - T_a)dt$$

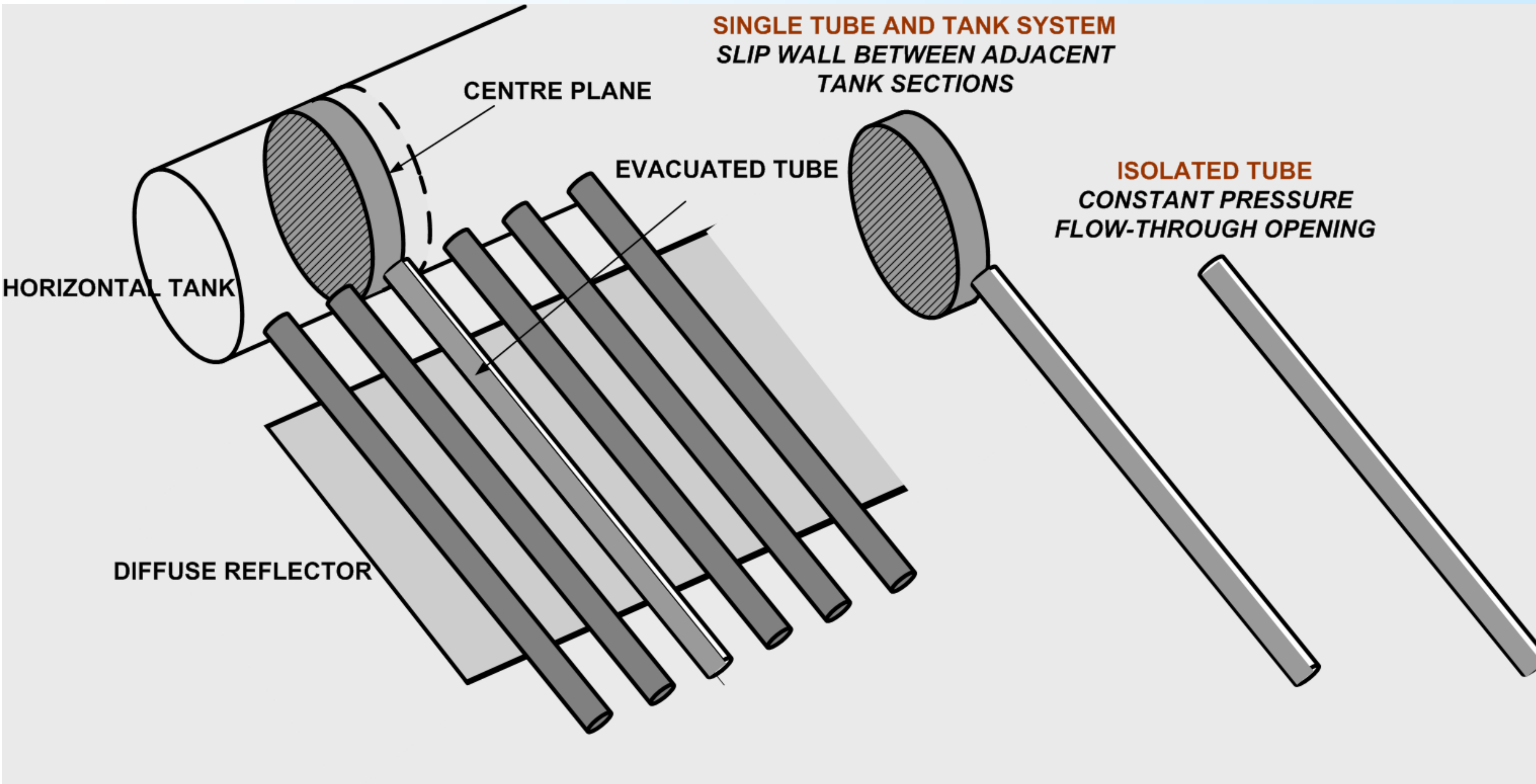
$$\dot{m} = \frac{Q_{u-collector}}{(21)c_p(T_{out} - T_{in})}$$

no. of tubes

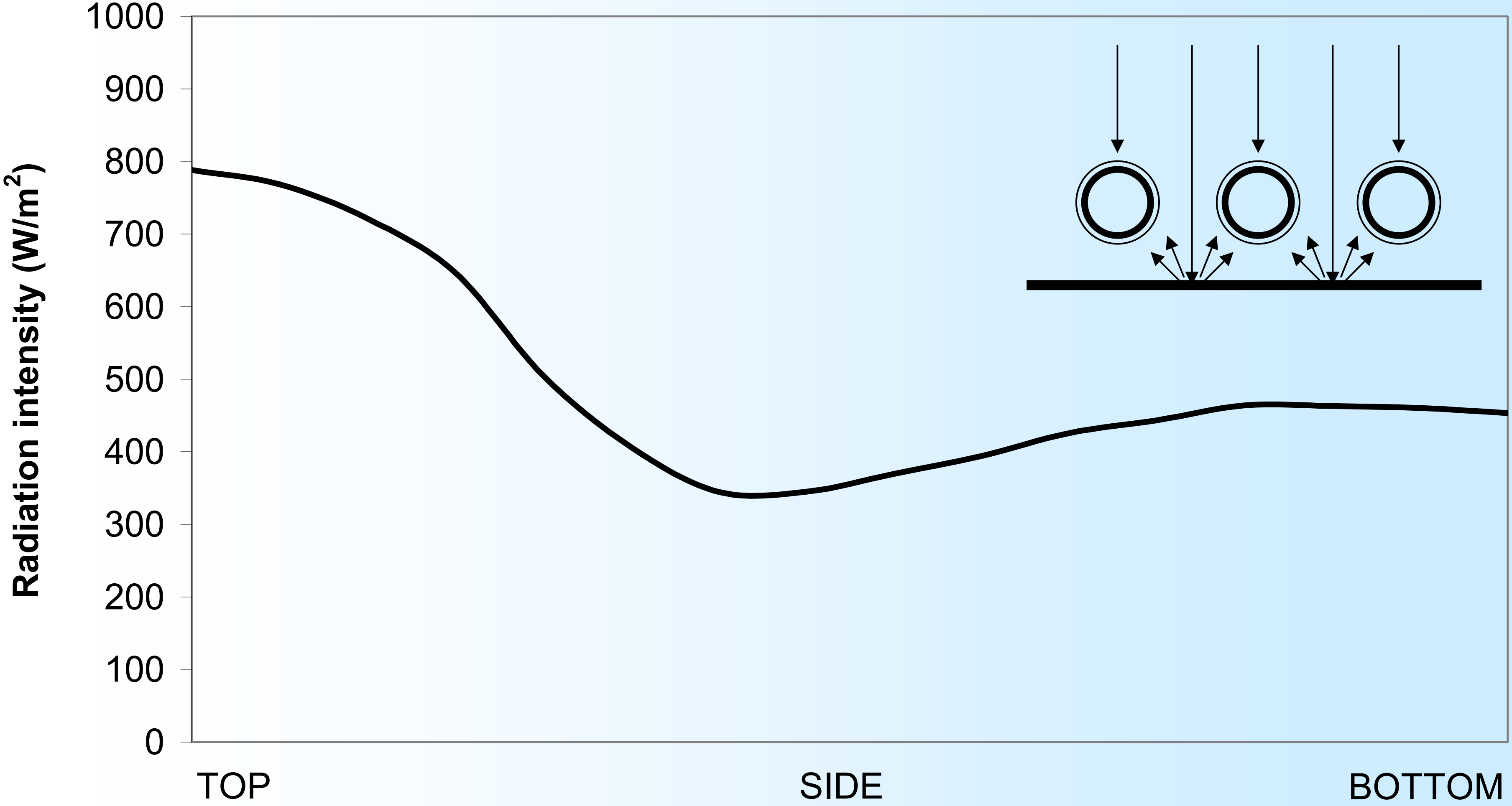
Outdoor experimental results



Evacuated tube collector CFD models



Circumferential solar flux distribution



Cabanillas et al. (1995), Renewable Energy 6, 843-847

Range of operating conditions investigated

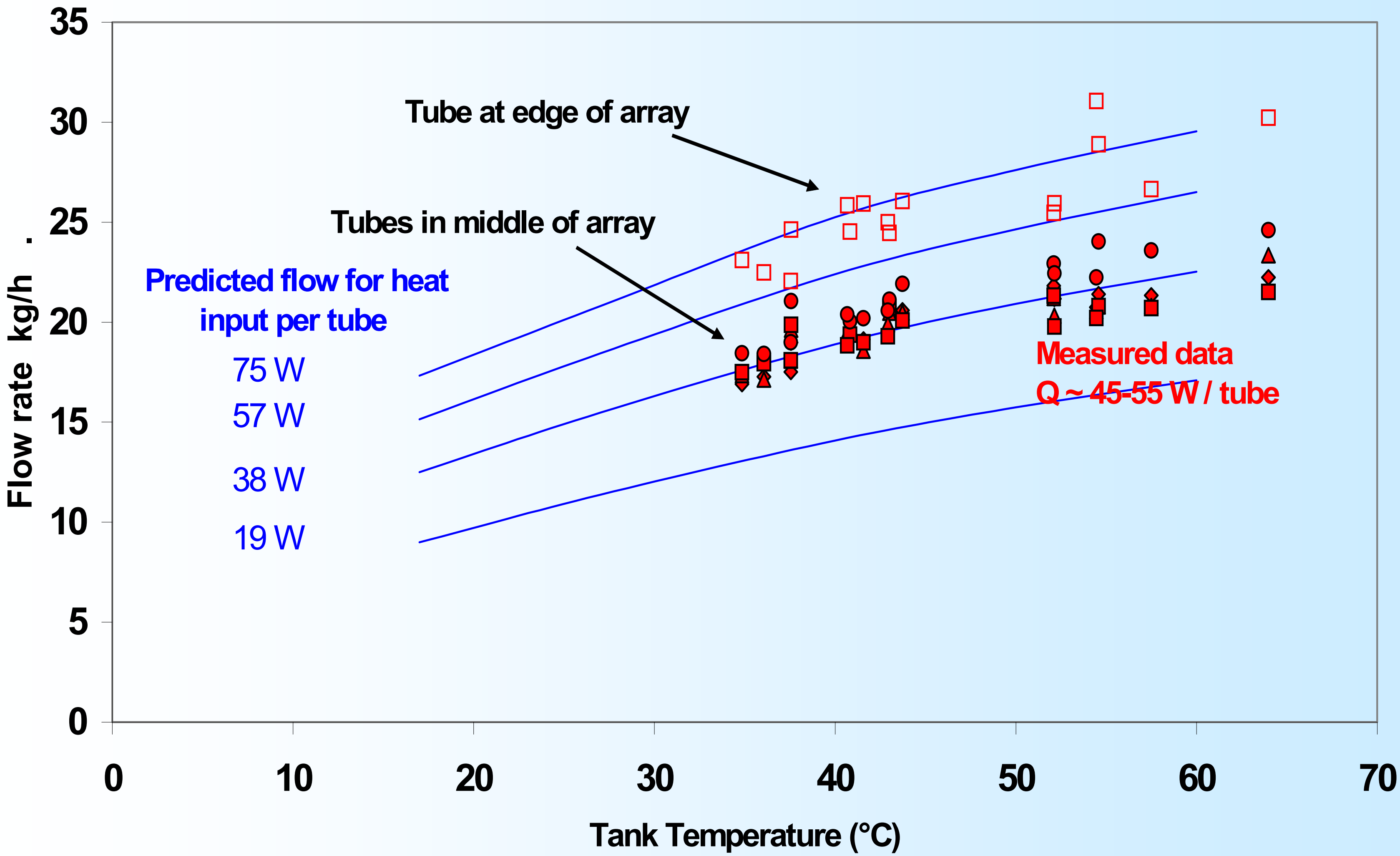
EXPERIMENTAL

- Collector inclination 45º, tube length-diameter ratio 80 (fixed)
- Heat input: 45-55 W / tube
- Tank temperature: 30-70 ºC

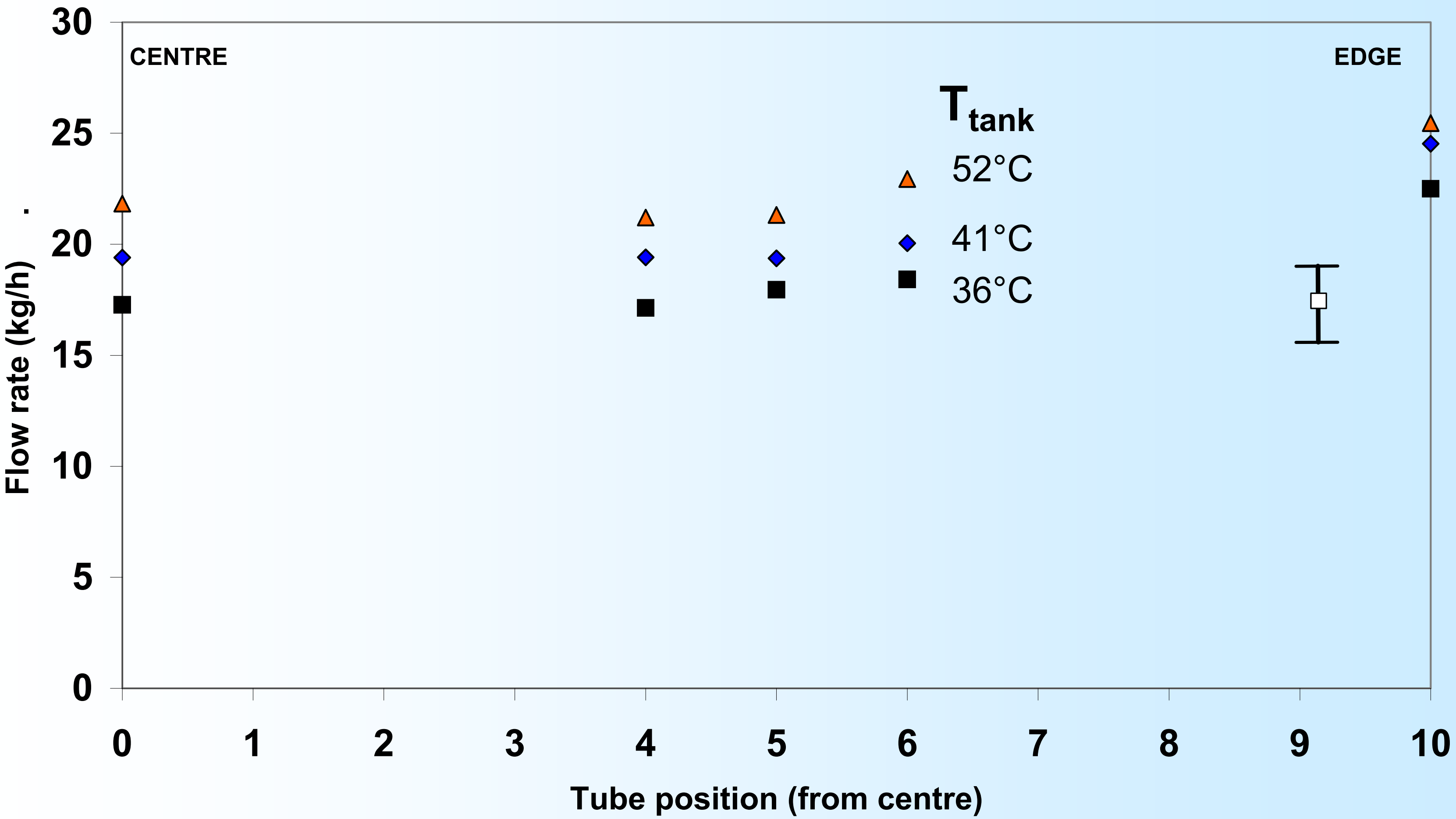
NUMERICAL

- Heat input: 125, 250, 375, 500 W/m^2 (19-75 W / tube)
- Tank temperature: 17, 27, 40, 50, 60 ºC
- Collector inclination: 30, 45, 70º to vertical
- Length-diameter ratio: 40, 80, 120

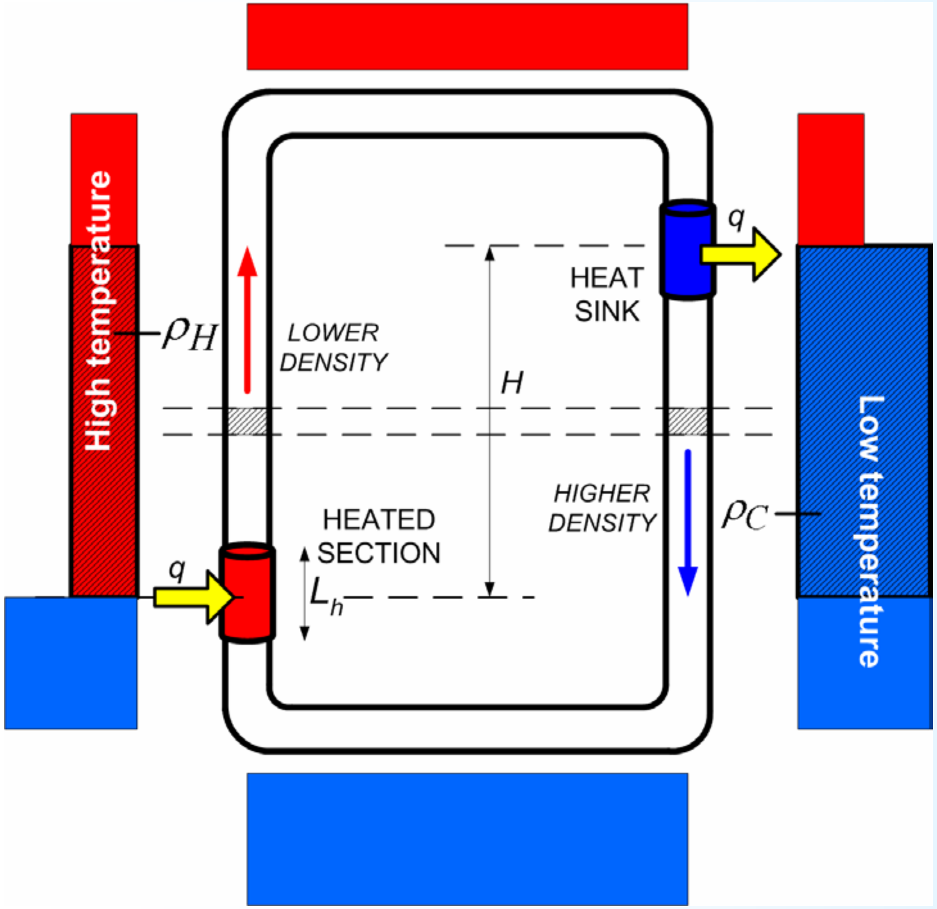
Measured and simulated flow rate through single-ended evacuated tubes



Circulation flow rate variation across the tube array



Non-dimensionalisation of circulation flow rate



Driving pressure due to buoyancy:

$$\Delta P = \int_{\Delta h} dp = \frac{4g\bar{\beta}qH}{u\pi d^2 c_p}$$

Friction pressure drop:

$$\Delta P_f = \frac{2f\rho u^2 L_p}{d} \qquad \Delta P_f = 32\mu u L_p / d^2$$

$$\boxed{\Delta P = \Delta P_f} \longrightarrow q = \frac{8\mu u^2 \pi c_p L_p}{\beta g H}$$

Heat transfer coefficient in the heated section:

$$\bar{h} = \frac{q}{A_s (T_w - T)_{avg}} \qquad \bar{h} = \frac{8\mu u^2 c_p L_p}{\beta g H d L_h (T_w - T)_{avg}}$$

Correlation function

Non-dimensional parameters:

$$Nu = \frac{\bar{h} d}{k}$$

$$Gr = \frac{g\beta(T_w - T_\infty) d^3 \rho^2}{\mu^2}$$

$$Pr = \frac{c_p \mu}{k}$$

$$Re = \frac{\rho u d}{\mu}$$

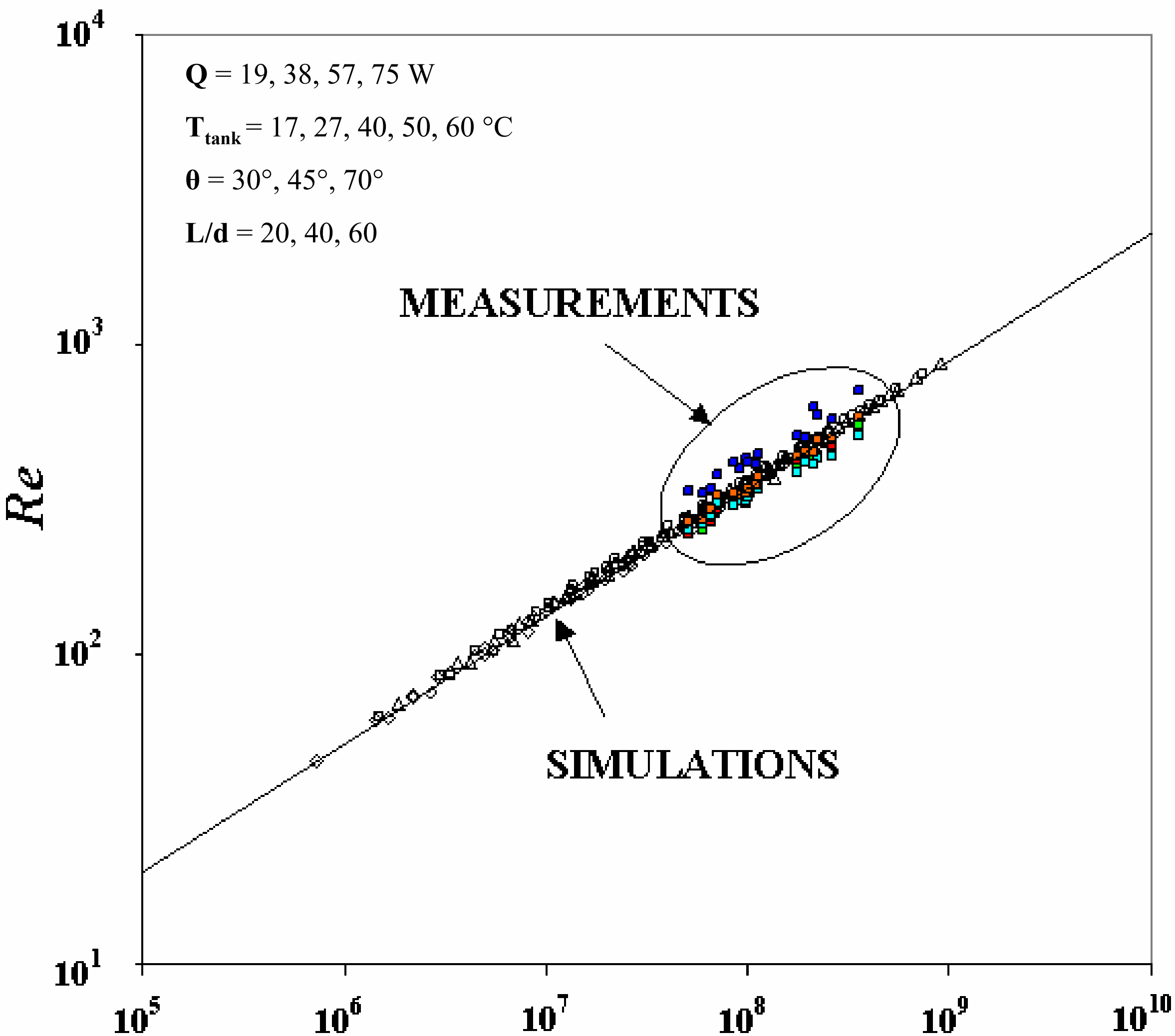
$$\bar{h} = \frac{8\mu u^2 c_p L_p}{\beta g H d L_h (T_w - T)_{avg}}$$

Substituting non-dimensional parameters:

$$Nu = \left(\frac{8dL_p}{HL_h}\right)\frac{Re^2 Pr}{Gr} \longrightarrow Re = \mathrm{X}\left(\frac{Nu.Gr}{Pr}\right)^{0.5}$$

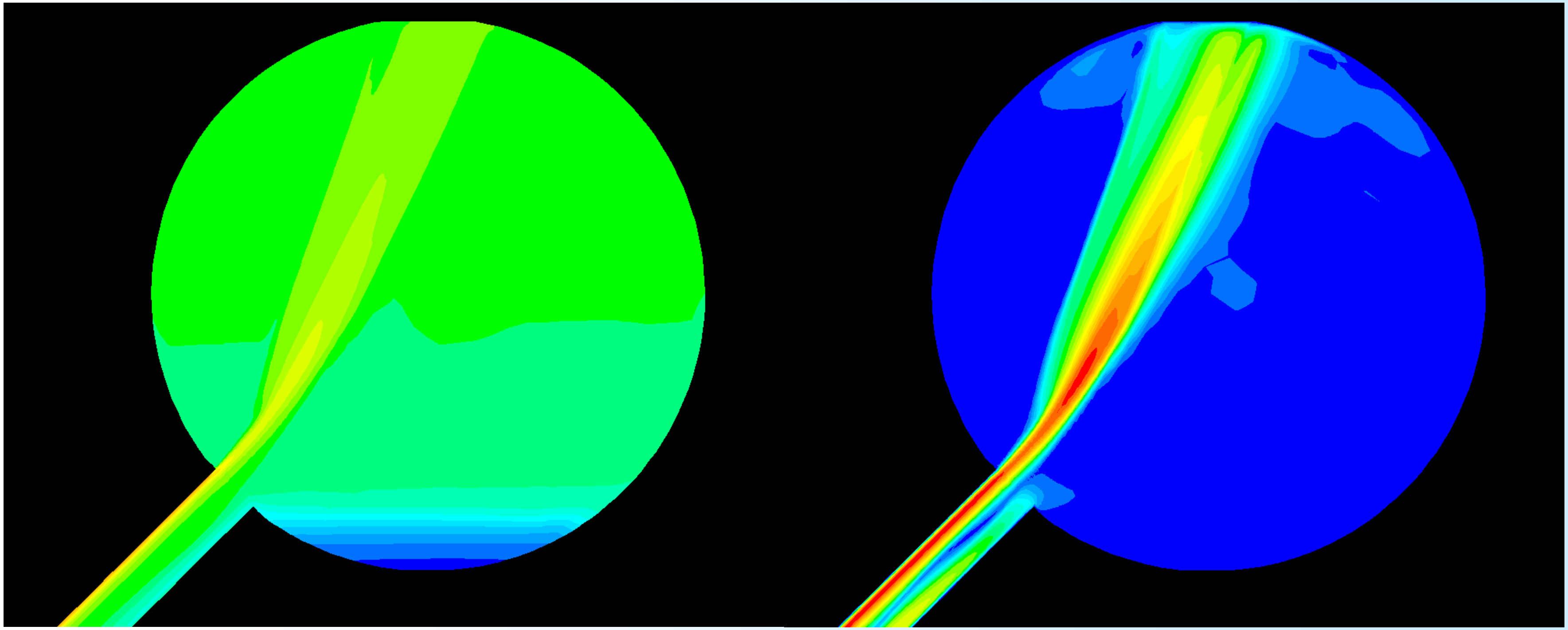
$$\mathrm{Re_d} = a_0\left[\frac{Nu_d.Gr_d}{\mathrm{Pr}}\cos\theta\left(\frac{L}{d}\right)^n\right]^{a_1}$$

Correlation of computed and measured flow rate and heat input



$$\frac{Nu.Gr}{Pr}(\cos\theta)\left(\frac{L}{d}\right)^{1.2}$$

Tube & tank interaction during peak solar radiation conditions



TEMPERATURE   VELOCITY

Concluding remarks

- High circulation flow rate through water-in-glass evacuated tubes
- Flow rate across the tube array is uniform, except for tubes near the edge of the array (perhaps!)
- New flow rate correlation developed for evacuated tubes mounted over a diffuse reflector
- Control of flow rate to promote tank thermal stratification may improve system performance
- Energy delivery of good quality evacuated tubes is not as sensitive as flat plate collectors to tank stratification, however recovery rate of delivered water temperature is still influenced by stratification