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MEASUREMENT OF LOCAL HOT-WALL HEAT TRANSFER IN HIGH-RAYLEIGH NUMBER FREE CONVECTION FLOW

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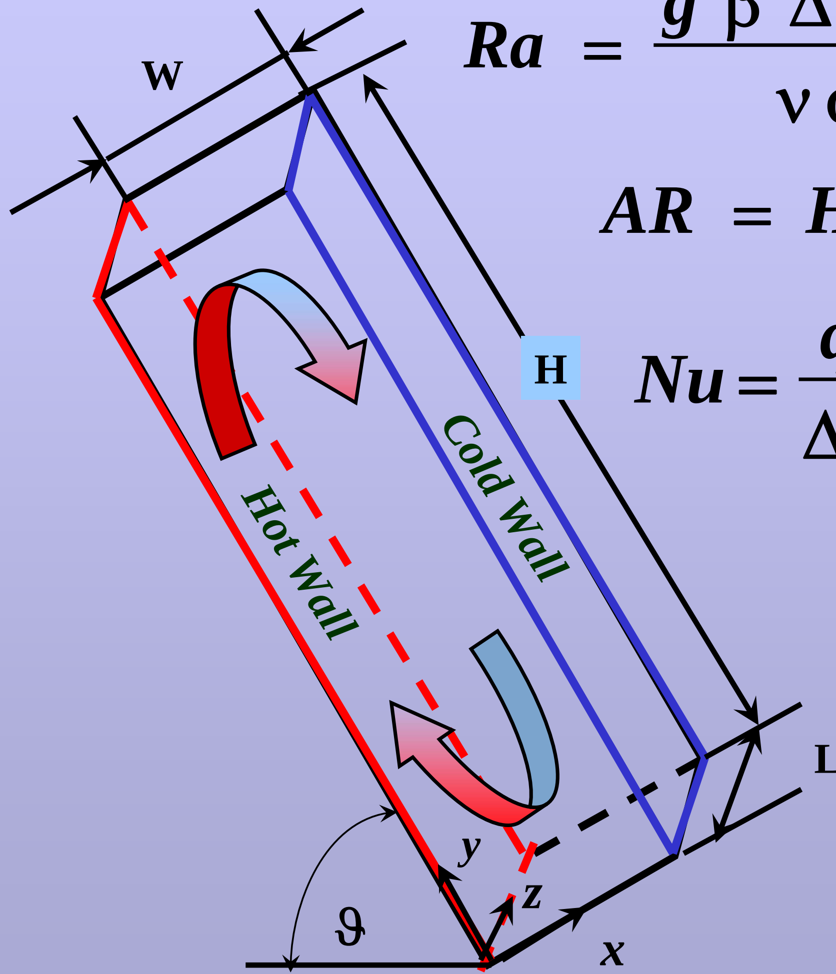
Abstract

- ***Previous work described a computer-controlled, electrically heated test rig, which allows the measurement of the local heat transfer coefficient along the hot wall in vertical or inclined enclosures at high Rayleigh number using thin-foil heat flow sensors.***
- ***A set of experiments were conducted using water as the working fluid in order to study the variation of the Nusselt number profiles with Rayleigh number and cavity inclination angle.***
- ***The tests described here cover a wide range of angles from Rayleigh-Bènard convection to stable thermal stratification, for an aspect ratio of 4. Results are compared with available experimental and numerical data presented in the literature.***

Introduction to Natural Convection



$$Ra = \frac{g\,\beta\,\Delta t\,W^3}{\nu\,\alpha}$$

$$AR = H / W$$

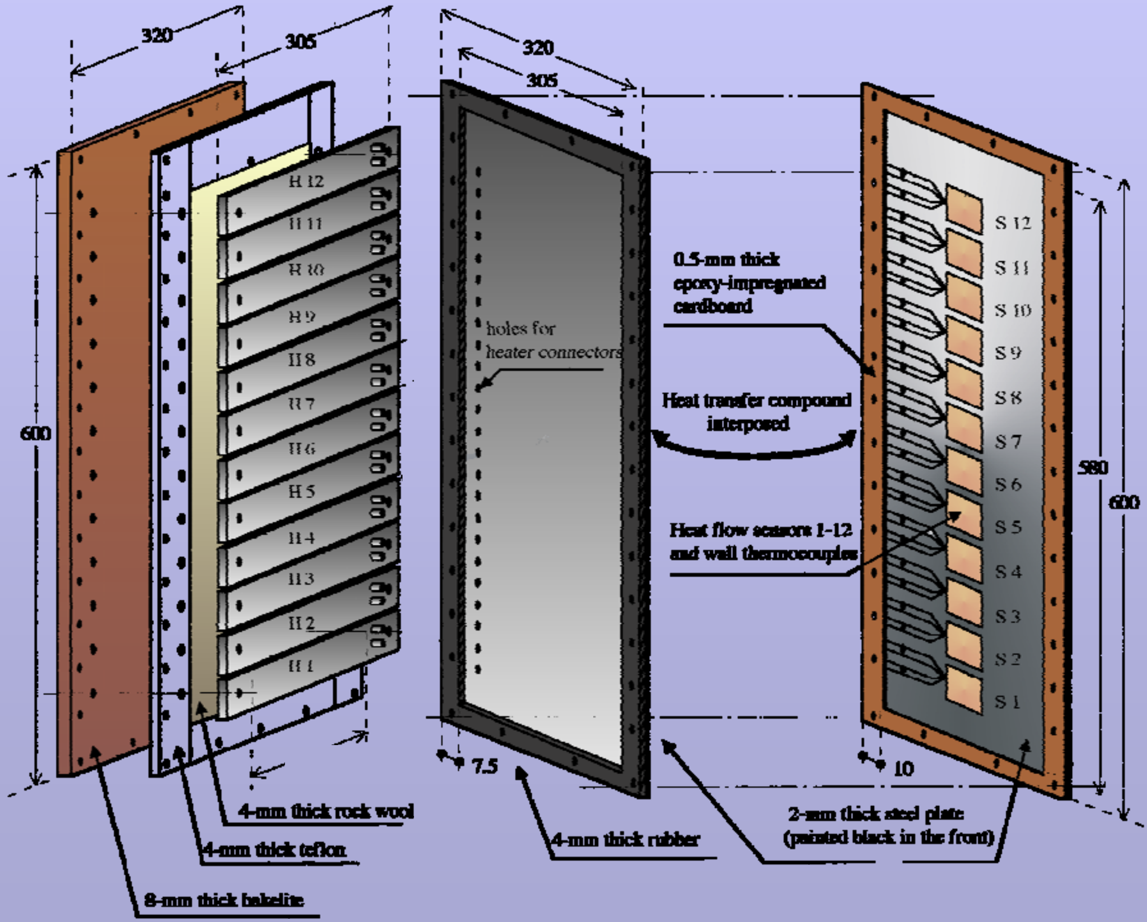
$$Nu = \frac{q}{\Delta t}\,\frac{W}{\lambda}$$

$$\vartheta$$

- *Confined buoyancy driven* ***convection****, as sketched in the figure for the case of a* ***rectangular enclosure****, has been the subject of many experimental, numerical and analytical studies because of its relevance in science and engineering.*
- *An experimental research program was initiated with the explicit purpose of measuring the* ***distribution of the local heat transfer coefficient*** *along the hot wall in vertical or inclined enclosures at high Rayleigh number.*
- *Following preliminary investigations based on the use of thin foil heat flow sensors and of water as the working fluid, a new and improved test apparatus was built as reported at UIT '98, and briefly described below.*

Experimental Method - a)

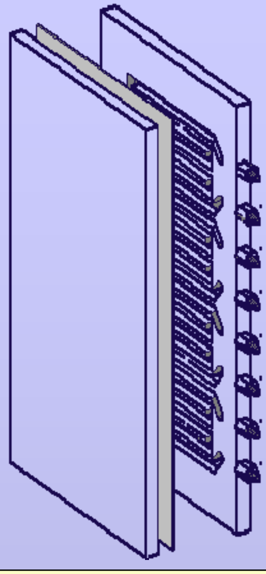
The cavity test section proper consists of a hot and a cold wall separated by perspex front-back and top-bottom walls. It was designed for the use of water or other liquids (e.g. glycerol or silicone oil) as the working fluids.



- *In order to measure the local value of the heat flux, 12 RdF heat flow sensors of the thin-foil type, equipped also with a wall thermocouple, are interposed between two 2-mm stainless steel sheets, one of which faces the fluid while the other is back-heated by 12 Watlow flat resistance heaters.*
- *The heaters are independently controlled by a PC via solid state relays, so as to maintain a prescribed wall temperature or heat flux profile. Their total power is ~3.6 kW.*

Experimental Method - b)

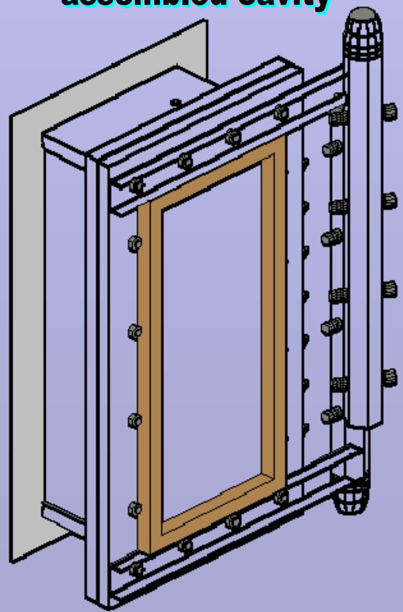
Exploded View of the cold Wall



- *The cold wall consists of a 20 mm thick aluminium slab, kept at a uniform temperature by forced circulation of water in milled grooves.*
- *A large (300l) water tank which acts as a thermal flywheel and is refrigerated, in turn, by a 4-kW Corema industrial chiller via a copper coiled-tube heat exchanger.*

- *The enclosure proper is completed by 4 Perspex walls. The maximum size of the active region of the hot and cold walls is **48x24 cm**, and the distance W between the two walls can be made to vary between a few mm and **12 cm**.*
- *If the working fluid is water, and the hot-to-cold wall temperature drop varies up to a maximum of 40°C, **Rayleigh numbers** in the range of **~10^7** to **~10^9** (based on W) can be obtained.*
- *The whole assembly is mounted on a swinging table which allows arbitrary inclination angles to be achieved, from **0°** (Rayleigh-Bènard convection) to **180°** (stable thermal stratification with the hot wall at the top). The latter condition, under which heat transfer occurs by conduction only, was used to calibrate the heat flow sensors.*

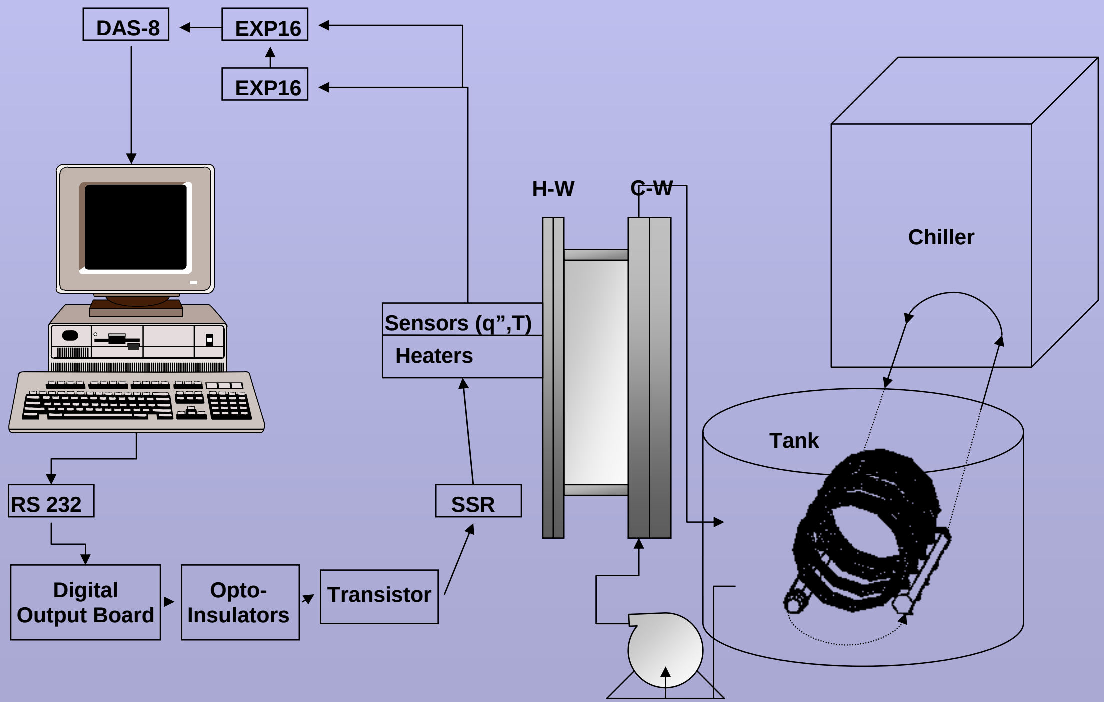
Overall view of the assembled cavity



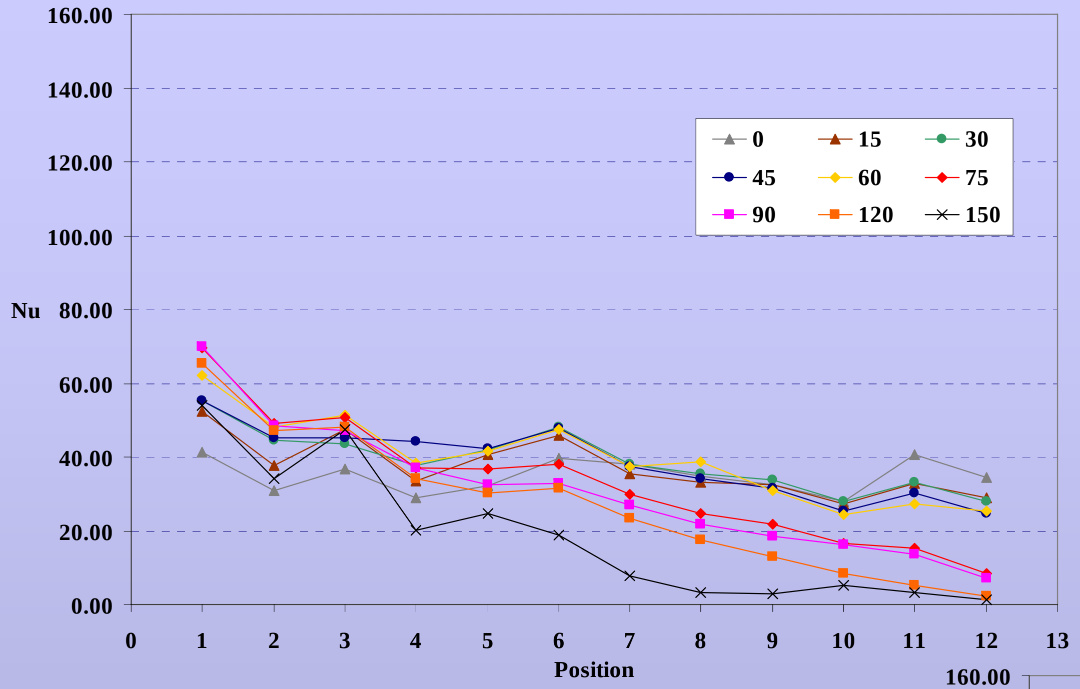
Experimental Method - c)

The resulting signals from thermocouples and heat flow sensors are acquired by a 486 PC via two 16-channel Keithley MetraByte EXP-16 multiplexer-preamplifiers and signal conditioners and a Keithley DAS-8 12-bit A/D converter. The overall resolution of the acquisition system is 2.44 μV, corresponding to ~12 W/m^2 in terms of heat flux.

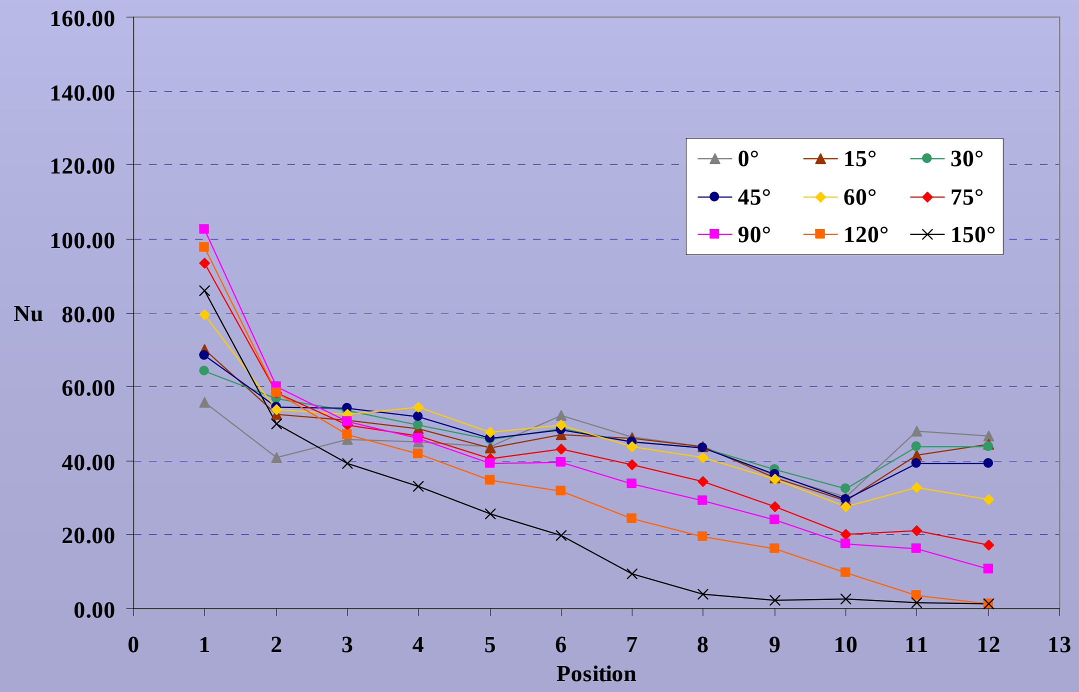
Block diagram of the measurement/control system



Results - a) *Nu* profiles for different angles ϑ

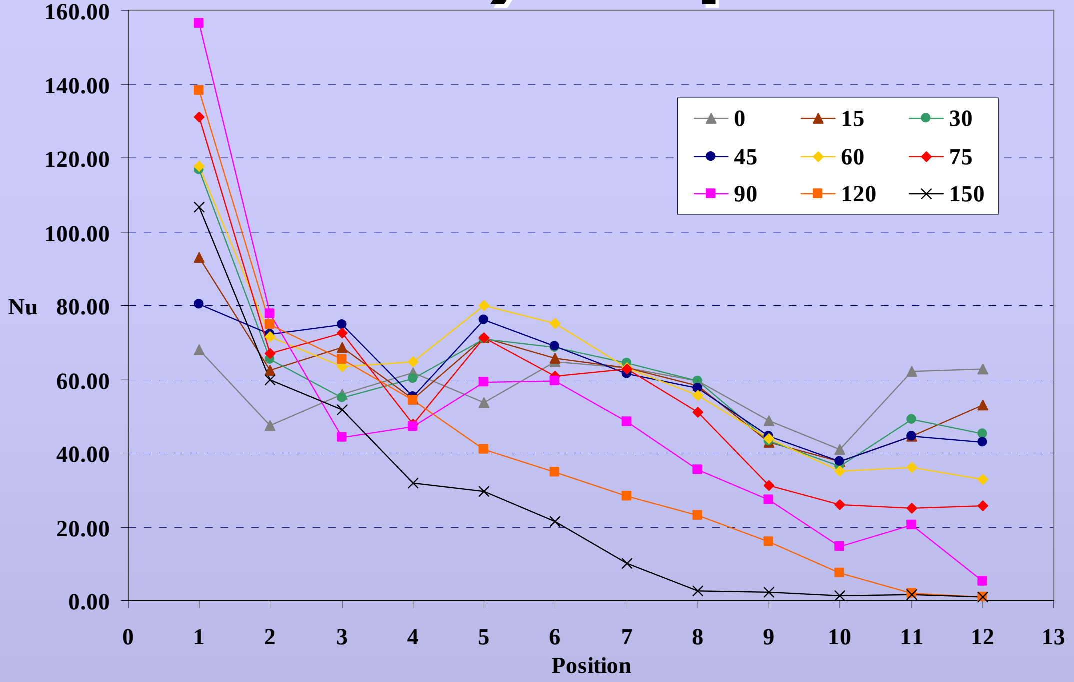


Nu profiles for a cavity of ***AR=4*** *and different inclination angles.*
ΔT=5 K ***Ra=1.73×10⁸***.



Nu profiles for a cavity of ***AR=4*** *and different inclination angles.*
ΔT=10 K ***Ra=3.46×10⁸***.

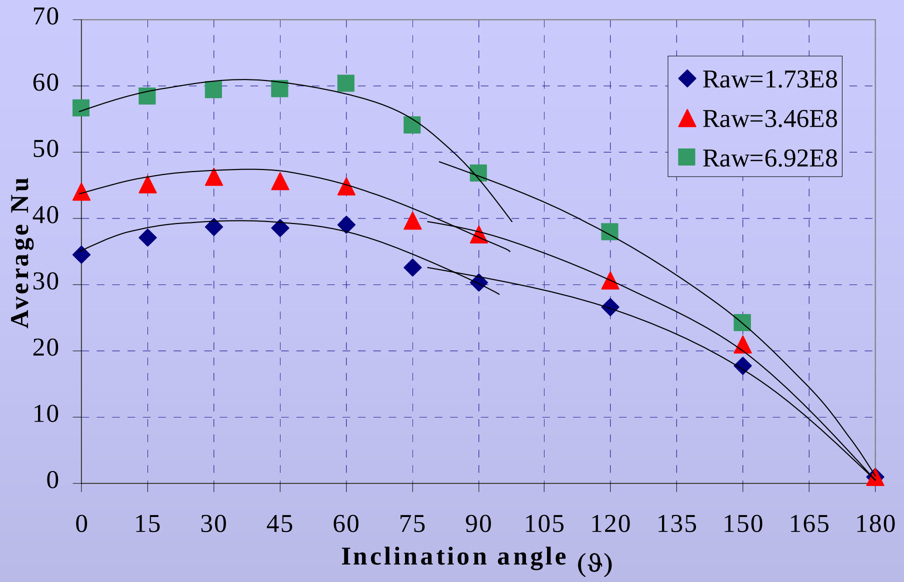
Results - b) *Nu* profiles for different angles ϑ



*Nu profiles for a cavity of **AR=4** and different inclination angles.*
ΔT=20 K   Ra=6.92×10^8.

- *For all angles but ϑ=0° Nu decreases from bottom to top as one moves along the hot wall.*
- *As the inclination increases from 0° towards 180°, the Nu maximum, attained at the location of the first sensor, increases up to ϑ=90° (vertical cavity) and then decreases. On the contrary, the value of Nu on the opposite end of the wall (sensor 12) decreases monotonically with ϑ.*
- *Profiles obtained for ΔT=20 K and 15°≤ϑ≤90° exhibit a broad local maximum, located roughly at position 5÷6.*
- *The fact that a local maximum is found only for high Ra suggests that it is associated with instabilities of the hot wall boundary layer. This is confirmed by crude flow visualisations which show the appearance of irregularities ("ripples") in the BL at y~0,3÷0,5 H.*
- *Previous findings of local maxima of Nu in experimental studies were reported by our group. Similar maxima were obtained by different authors in numerical simulations for square cavities at high Ra (>10^{10}) using the k-ε turbulence model and adiabatic end wall boundary conditions.*

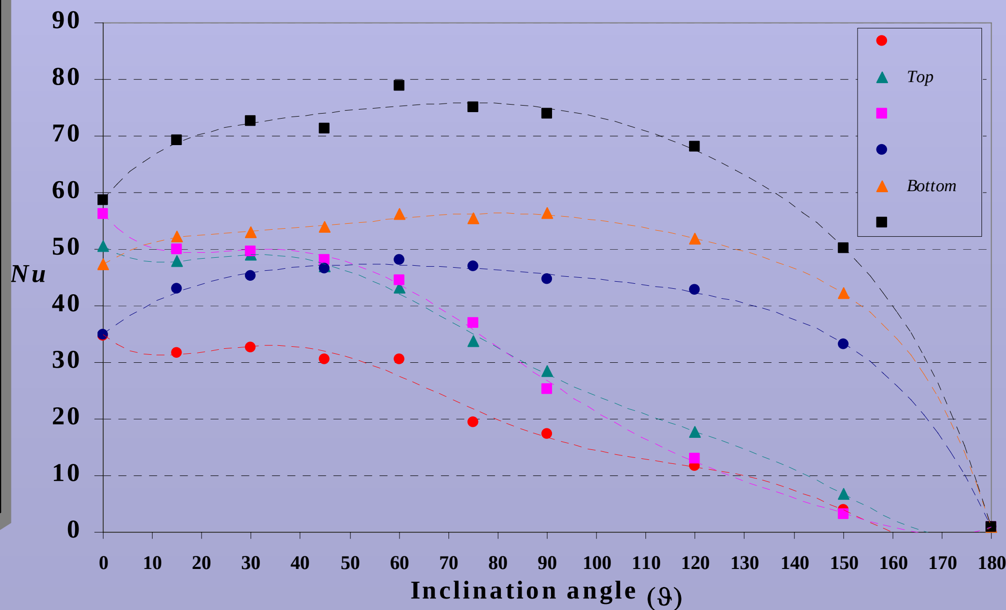
Results - c) *Nu* average for different angles ϑ



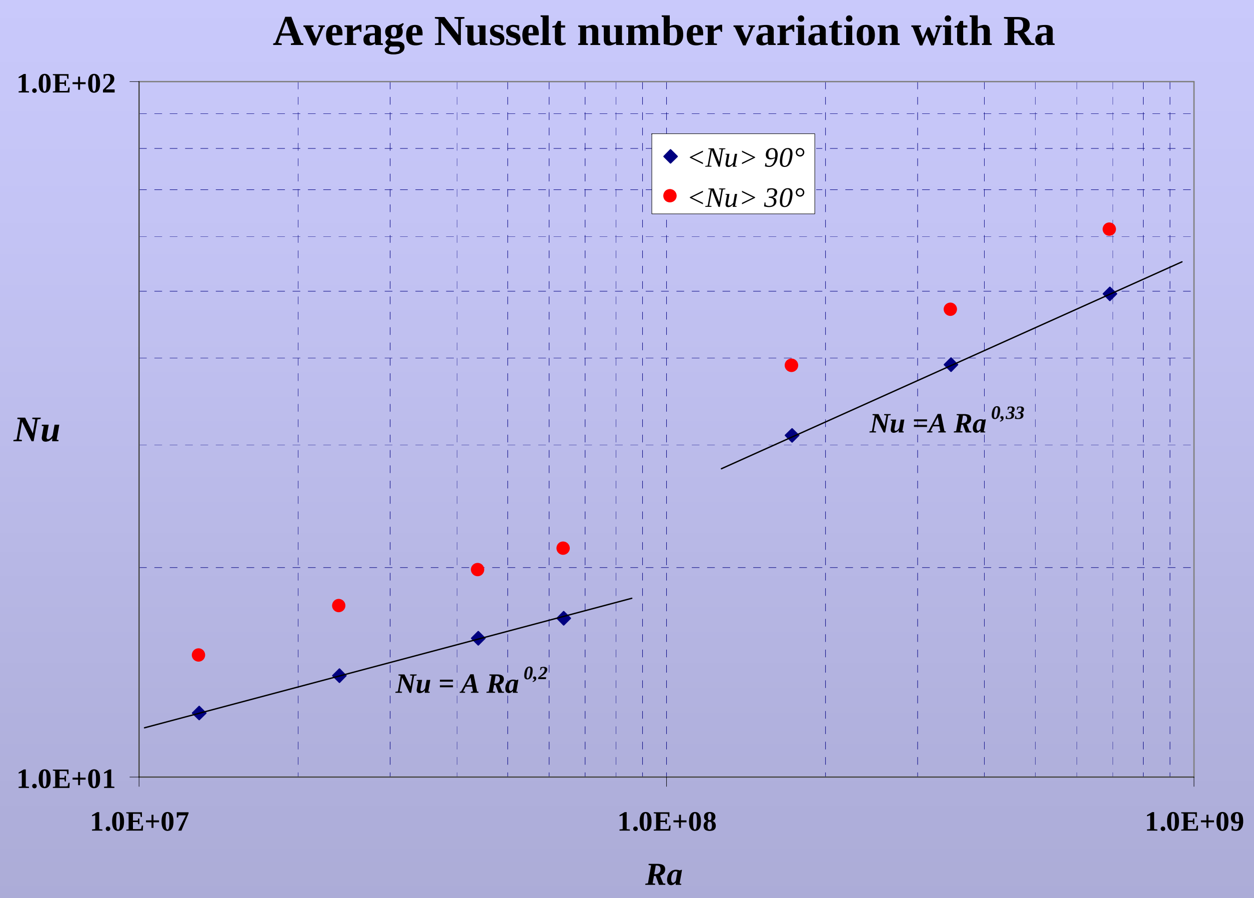
- *The figure reports the average Nusselt number as a function of ϑ for different values of Ra.*
- *The experimental trend suggests the existence of a change of slope in <Nu> for ϑ between 75° and 90°, in agreement with literature data as reviewed, for example, by Catton [1978] (laminar flow at Ra≤10^6).*
- *A similar dependence of <Nu> on ϑ was also experimentally obtained by Nishimura et al. [1990] for the same aspect ratio (four) and working fluid (water) at Rayleigh numbers ranging between 3×10^7 and 7×10^7.*

- *The different role played by the* ***bottom*** *and* ***top regions*** *of the hot wall in the overall dependence of <Nu> upon the inclination angle can be deduced from the behaviour of the Nu profiles in previous figures.*
- *It was better evidenced in the figure besides by reporting the two averages of Nu taken over the bottom half (sensors 1÷6) and the top half (sensors 7÷12) of the hot wall.*

●,❍: *Ra*=1.73×10^8; ♦,Δ: *Ra*=3.46×10^8;
■,□: *Ra*=6.92×10^8



Results - d) *Nu* average as a function of *Ra*



- *The figure besides reports the average Nusselt number as a function of Ra for* ϑ*=30° and 90°.*
- *It includes previous results obtained by our group for lower Rayleigh numbers using a different test section, so that the overall range of Ra covered extends from* 1.3×10^{7} *to* 6.92×10^{8}*.*
- *A least-square best fit of the data by a power law* $\langle Nu\rangle = A\,Ra^{n}$ *provides* $n\approx0.2$ *in the lower range* $Ra<10^{8}$ *and* $n\approx0.33$ *in the upper range* $Ra>10^{8}$*, with only a minor influence of the inclination angle.*
- *The power law exponents are in agreement with experimental correlations presented in the literature.*

CONCLUSIONS

- *Nusselt number profiles along the hot wall for free convection in a rectangular enclosures of aspect ratio 4 were obtained for inclination angles ϑ ranging from 0° (Rayleigh-Bénard convection) to 180° (stable thermal stratification with the hot wall at the top) and for three values of the Rayleigh number.*
- *For the higher values of Ra a local maximum was observed in the profiles, in agreement with numerical simulations reported in the literature which used the $k-\varepsilon$ model.*
- *The average Nusselt number $\langle Nu \rangle$, once reported as a function of ϑ, showed a change of slope in correspondence to inclination angles between 75° and 90°.*
- *As regards the variation of $\langle Nu \rangle$ with the Rayleigh number, a least-square best-fit of data for different angles at $Ra > 10^8$ provided a power law $\langle Nu \rangle = A\ Ra^{0.33}$, in agreement with the literature, while data for lower values of Ra ($<10^8$) indicated a lower exponent (~0.2).*