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COOLING OF BUILDING INTEGRATED PHOTOVOLT/ VENTILATION AIR

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ABSTRACT

The conversion efficiency of solar cells is dependent on the cell temperature and they perform better the colder the cells are. The paper discusses cooling of solar cells by providing solar cell modules with an air gap behind the modules. The stack effect in the air gap drives the ventilation flow in a hybrid ventilation system. Expressions for the bulk flow properties (volumetric flow rate, mass flow rate and temperature) are presented as a function of the geometry of the air gap and the location of the heat input (configuration factor). The validity of the expressions is demonstrated by comparison against measurements from a mock up in the laboratory.

1 INTRODUCTION

Hybrid Ventilation is natural ventilation plus mechanical ventilation with the side condition that natural ventilation shall be used as much as possible to minimise the energy use. During the season with high solar irradiation cooling of buildings is required. At the same time the outdoor temperature is relatively high and subsequently the cooling capacity of outdoor air is low. The low cooling capacity can with respect to people's sensation of comfort be compensated by high air velocities. This requires supply of high flowrates of air to the building. In order to meet the requirements of supply of high flowrates a solar chimney can be used to provide a sufficient stack effect.

To boost the stack effect the solar chimney can be provided with a cladding absorbing the solar radiation, see Fig. 1. Most types of cells perform better at lower temperatures. Therefore cooling of solar cells is to be wished. The temperature can be reduced by active cooling methods (e.g. introducing water pipes behind the module) or by passive cooling methods. *Passive methods* can be applied in the following manner:

1.Providing the module with an air gap that allows air to flow behind the module. Heat is transferred by convection to the air and transported away by the airflow.

2.Connect the module to heat sinks (bodies with lower temperature). Heat is transported by conduction to heat sinks.

3.Provide the back surface of module with a coating of a suitable emissivity so heat is transported by radiation to neighbouring colder surfaces.

In the context of hybrid ventilation it is natural to use the ventilation air for cooling of the cells. The temperature of the cells will be *minimised* by *maximising* the flow rate in the air gap. This is in consort with the requirements of supply of high flowrates to meet the comfort requirements.

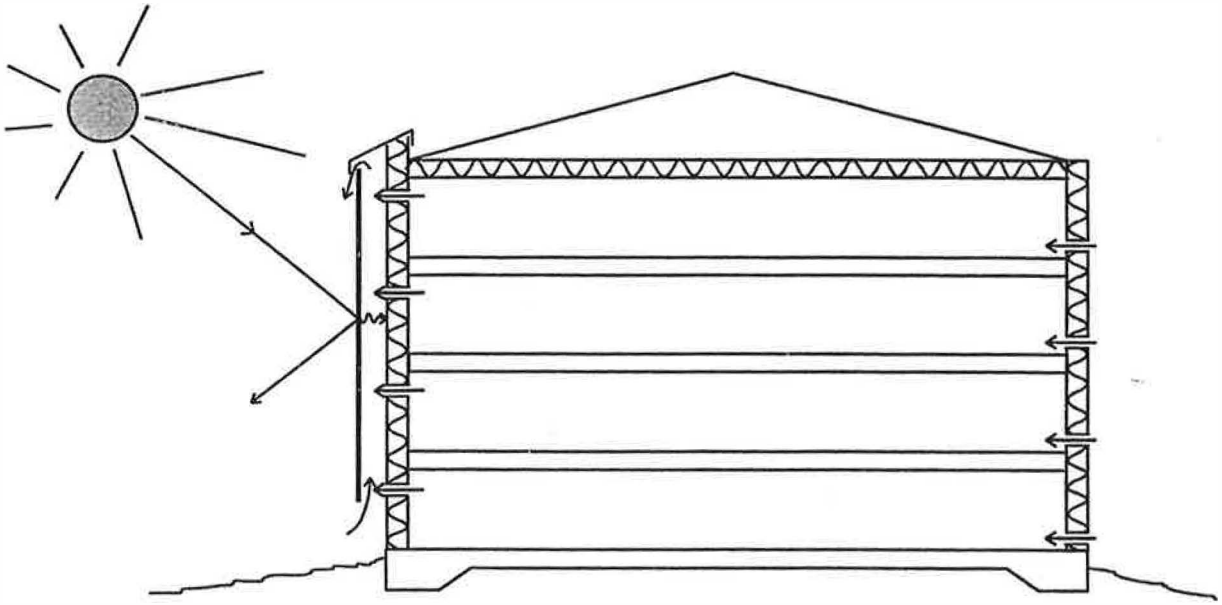


Figure 1 Schematic of a solar chimney provided with solar cell modules

2 TYPES OF SOLAR CELLS AND THEIR PROPERTIES

The solar cell operation is based on the ability of semiconductors to convert sunlight (photons) into electricity by exploiting the *photovoltaic effect*. Only a fraction of the absorbed solar radiation is converted into electric energy. The remaining part is dissipated as heat. The maximum possible efficiency is determined by the band-gap in the material. Only photons with energy higher than the band-gap give rise to the photovoltaic effect. All radiation below this energy is dissipated as heat and all excess energy of the active photons is also dissipated as heat. Typical values of the conversion efficiency (electrical power/ incident solar radiation) are 5-30 %, where the higher value is close to the maximum achievable, while 5 % is typical for inexpensive photovoltaic cells based on vacuum deposited amorphous silicon. The basic element is the cell and a module consists of a number of cells.

Table 1 Different types of solar cells [Karsten W (1999)].

Cell type	Properties
Amorphous silicon	Red brown or dark grey, opaque or semitransparent
Polycrystalline silicon	Blue, opaque, with light transmitting between cells, "high" efficiency
Monocristalline silicon	Blue or dark grey, with light transmitting between cells, "high" efficiency

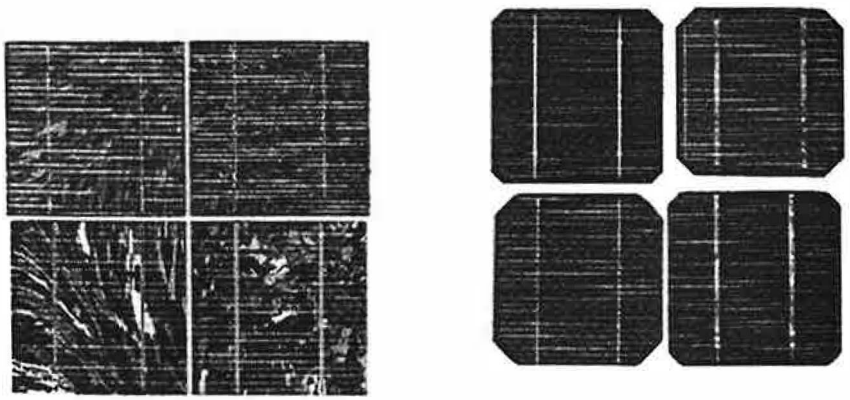


Figure 2 Muliticristalline silicon cells (L) and monocristalline silicon cells (R)

Solar cells are rated at Standard Test Conditions (STC) with a nominal cell operating temperature equal to T_0=25 °C and an irradiance of about 1000 W/m^2. The efficiency of many types of solar cells is dependent on the cell temperature, T_c, and the conversion efficiency , η, decreases with increasing temperature according a linear relationship

$$\eta = \eta_0 - \gamma(T_c - T_0)$$

For example *the relative temperature coefficient* γ of crystalline silicon solar modules is in the range 0.4 - 0.6 % K. With 13% absolute conversion efficiency this corresponds to an absolute temperature coefficient between 0.03 and 0.046%. For these types of cells a reduction by 20 °C will give rise to an increase in efficiency between 0.6 and 1%.

Therefore it is important to take precautions so unnecessary "overheating" of modules can be avoided. Ideally mounting the modules so they are freely exposed to ambient conditions can solve this.

In building integration a module is always mounted close to a surface and an increase in temperature will occur due to constrained airflow around the module and reduction in heat loss by radiation because of the presence of surrounding warm surfaces

3 BUOYANCY DRIVEN FLOWS IN VERTICAL DUCTS

Buoyancy (heat) and the wind-induced pressure difference between the top and bottom of the air gap drive the air. We will only consider flow induced by buoyancy. The flow is generated by a *total* heat input of q[watt]. For convenience (it gives shorter expressions) the total heat input will always be expressed in terms of the specific the *specific buoyancy flux,* $B = g\beta q/\rho C$ [m^4/s^3]. In an air gap with height H and crossectional area A the pressure available for *generating* a flow is given by the difference in mass Δm between the air in the air gap and a corresponding volume with ambient air.

$$\Delta p = \frac{g\Delta m}{A} = \frac{\alpha B}{\frac{\dot{m}}{\rho}} \rho H$$

Where α is the configuration factor that considers the effect of the location of the heat input to the air gap and $\dot{m}$ is the mass flowrate. Forces opposing the flow are friction and end losses at the top and bottom.

Due to the heating the density of the air decreases with increasing height and the velocity increases to keep the mass flow constant. This gives rise to an increase in momentum. However, the temperature increase from the bottom to the top is relatively moderate, and therefore the increase in momentum is very low and will be ignored.

From the PV panel heat is transferred to the air gap by convection. Radiative heat transfer carries heat (about 40 % of the heat input) from the PV panel across the air gap to the otherwise unheated wall. Thus radiation activates convection on the otherwise unheated surface. Therefore the originally single sided heated problem becomes a double sided heating problem.

To *minimise* the cell temperature is equivalent to *maximise* the flow rate in the air gap. Therefore air gaps shall be designed to maximise the airflow while maintaining an evenly distributed and stable flow. Non uniformly distributed airflow lead to the occurrence of "hot spots". Instability of the flow may lead to partly reversed flow.

For a given heat input the flow rate in the air gap, and therefore also he temperature, depends on the following geometrical parameters of the air gap

- Position of the solar cell module
- Thickness d of the air gap
- Aspect ratio H/d
- Type of inlet to the air-gap; sharp-edged or aerodynamically smooth

3.1 Position of the solar cell module –Configuration factor

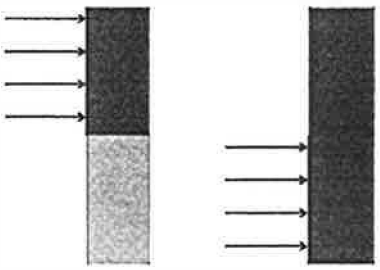
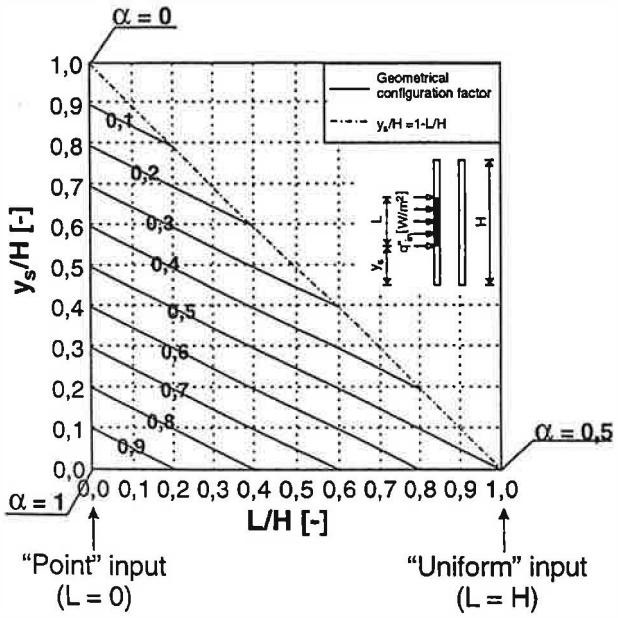


Figure 3 To maximise the flowrate the solar cell module shall be placed so the height of the heated air column (dark) is as large as possible

The effect of the distribution of the heat input B can be characterised by the *geometrical configuration factor* α. The heat input is expressed as αB where α takes value in the range 0 to 1.



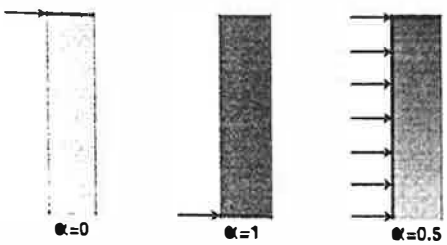


Figure 4 Geometrical configuration factor α *(Sandberg&Moshfegh(1999))*

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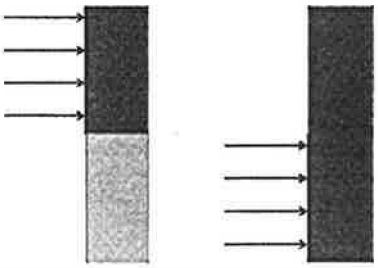

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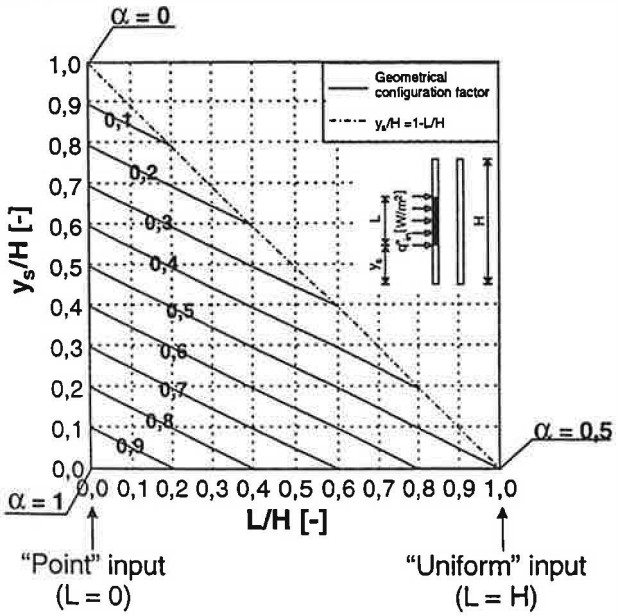

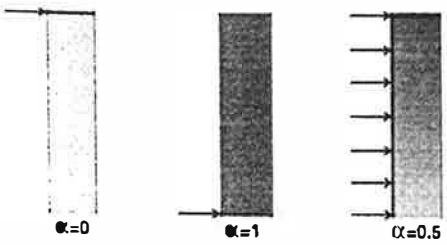

Figure 4 Geometrical configuration factor α *(Sandberg&Moshfegh(1999))*

The values given in Fig. 5 are valid for aspect ratios H/d> 60. For much lower values of the aspect ratio there is a redistribution of the heat input to other surfaces by radiation.

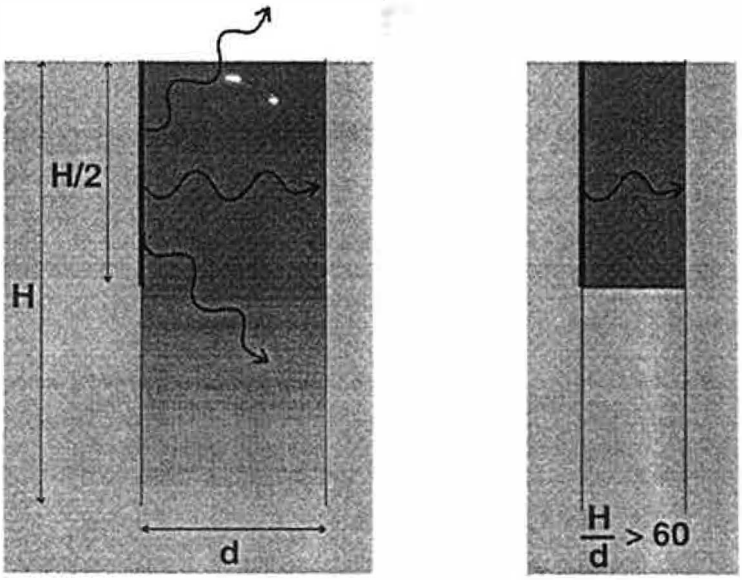

Figure 5 Effect of radiation *(Sandberg&Moshfegh(1999))*

3.2 Thickness of air gap

The thickness of the boundary layer δ in relation to the thickness d of the air gap is an important factor. There are two situations

- The separate boundary layers lining the bounding surfaces merge into one single profile after a certain distance, x_{est}. The flow is from then on fully established and the velocity profile is only a function of the y-coordinate.
- The duct is so wide that we have separate boundary layers along the whole height of the air gap. After a certain distance, x_{est} , the boundary layer thickness is constant and the velocity is only a function of the y-coordinate.

The assumption made here is that the length of the zone, x_{est}, to where the individual boundary layers forming on each side merge into one single profile is much shorter than the length of the air gap, $x_{est}/H<<1$.

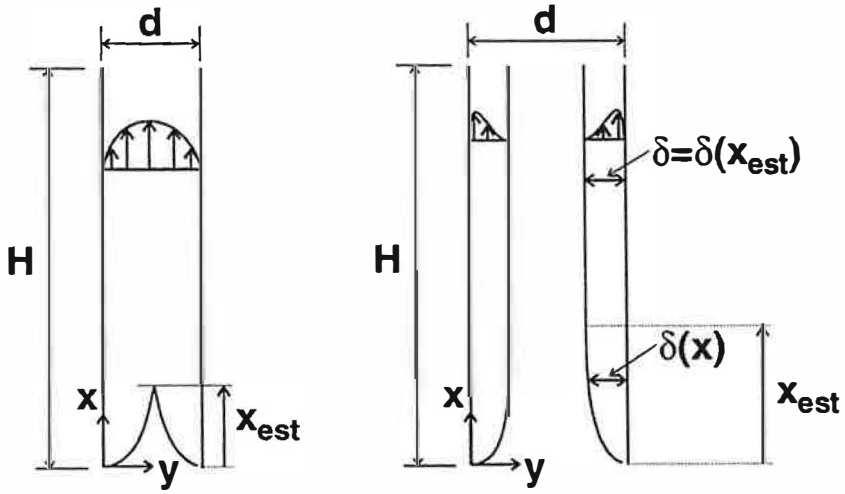

Figure 6 Boundary layers

3.3 Theoretical expressions for bulk flow properties

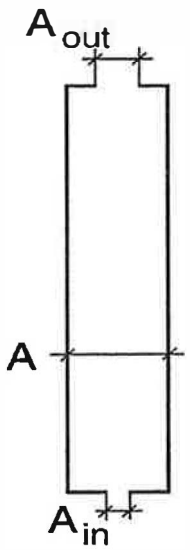

Figure 7 Notation

Turbulent flow or flow constrained by large losses at inlet or outlet

The equations valid for turbulent flow and when the flow is governed by the losses at the inlet ($A_{in}/A<<1$) or outlet ($A_{out}/A<<1$) are presented below. The flow averaged velocity inside the channel is equal to

$$U = (\frac{\alpha B}{\psi})^{1/3}$$

where $\psi = \frac{A}{H}[\lambda_{fric}\frac{H}{d} + \frac{1}{2}[(1+k_{in})\left(\frac{A}{A_{in}}\right)^2 + \left(\frac{A}{A_{out}}\right)^2]]$

The volumetric flowrate and mass flowrate are

$$Q = (\frac{\alpha B}{\psi})^{1/3} A$$

$$\dot{m} = \rho(\frac{\alpha B}{\psi})^{1/3} A$$

The temperature rise $\Delta T = T_{out} - T_{in}$ is

$$\Delta T = \frac{B}{\dot{m} g\beta} = \frac{1}{Ag\beta}\frac{B^{2/3}}{(\frac{\alpha}{\psi})^{1/3}}$$

The theoretical maximum flowrate and cooling is obtained when ψ attains it minimum value $\psi_{min} = A/H$. This occurs when there are no losses and the opening areas at the end are equal to area of the air gap. The maximum velocity is

$$U = (\alpha \frac{B}{w} \frac{H}{d})^{1/3}$$

and the corresponding temperature difference

$$\Delta T = \frac{1}{A^{2/3} g\beta} \frac{B^{2/3} H^{1/3}}{(\alpha)^{1/3}}$$

If one increases the height while keeping the thickness, d, of the air gap and the heat input constant the flowrate increases until it is constrained by friction, the *absolute maximum* velocity is attained.

$$U_{max} = (\frac{\alpha \frac{B}{w}}{\lambda_{fric}})^{1/3}$$

where λ_{fric} is the friction coefficient.

The effect on the flowrate of change of geometry on the air gap is summarised in Fig. 8.

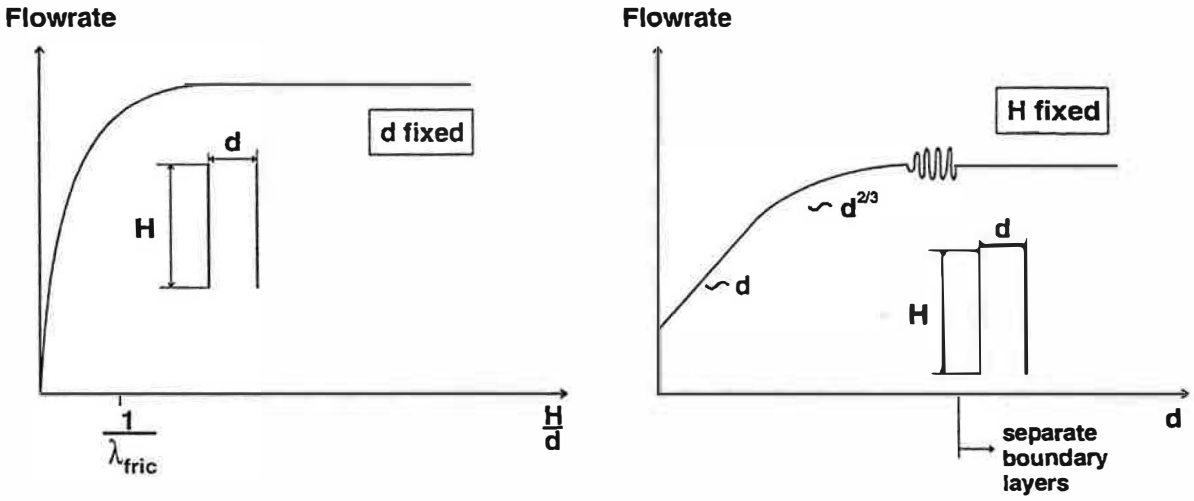

Figure 8 Expected effect of change of geometry (turbulent flow)

Laminar flow

For a very narrow air gap laminar flow may occur. For a balance between friction (kinematic viscosity ν) and buoyancy the flow averaged velocity becomes

$$U_{max} = (\frac{\alpha \frac{B}{w}}{12 \frac{\nu}{d}})^{1/2}$$

4 EFFICIENCY OF A SOLAR CHIMNEY

The purpose of the solar chimney is to generate a flow rate i.e. to generate kinetic energy. One can define a conversion efficiency as the ratio between the kinetic energy of the flow in the chimney and the flux of heat in the chimney.

$$\text{Conversion efficiency} = \frac{\text{Kinetic energy}}{\text{Heat flux}} = \frac{\frac{1}{2}\dot{m}U^2}{q}$$

In terms of the relations for mass flow and velocities derived in section 3.3 the conversion efficiency becomes

$$\frac{\frac{1}{2}\rho\frac{\alpha B}{\psi}A}{q}$$

After introducing the maximum value of α and the min value of ψ it becomes

$$\frac{gH}{TC_p}$$

For a chimney with height 10 m the conversion efficiency is 0.033 % which is much less than the conversion efficiency for solar cells.

5 EXAMPLES

We will consider an air gap with height H=6.5 m and A=wxd=1.64mx0.23m (Sandberg&Moshfegh(1996)). The aspect ratio is H/d=28. The air gap is heated along its whole height (α=0.5). Two cases are shown:

Both ends open: $A_{in} = A_{out} = A$

Constrained at the top: A_{in} = A and A_{out} / A=4 %.

In the theoretical predictions the parameters have been set; λ_{fric}=0.028 and k_{in}=0.5.

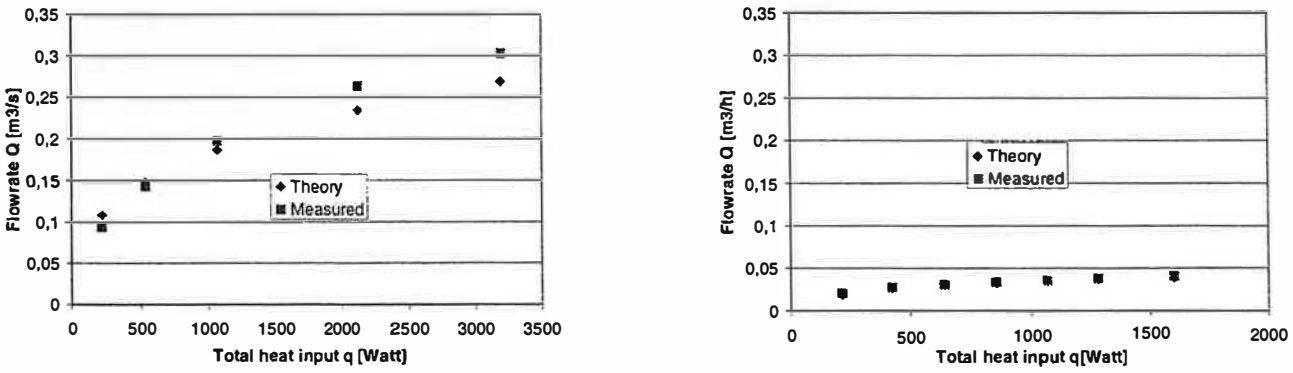

Figure 9 Comparison measurements and predictions
***Left*: Both ends open *Right*: Constrained outlet**

For the constrained outlet the relative difference between measurements and predictions is, except for the first point, within 4 %. With both ends open the relative difference is on average 10 %.

The next figure shows, based on simulation, assuming turbulent flow, results a comparison in cell temperature when a module is mounted flush to a wall or provided with a 5 cm air gap. The height is 5 m and the temperature shown is the average temperature over the whole height.

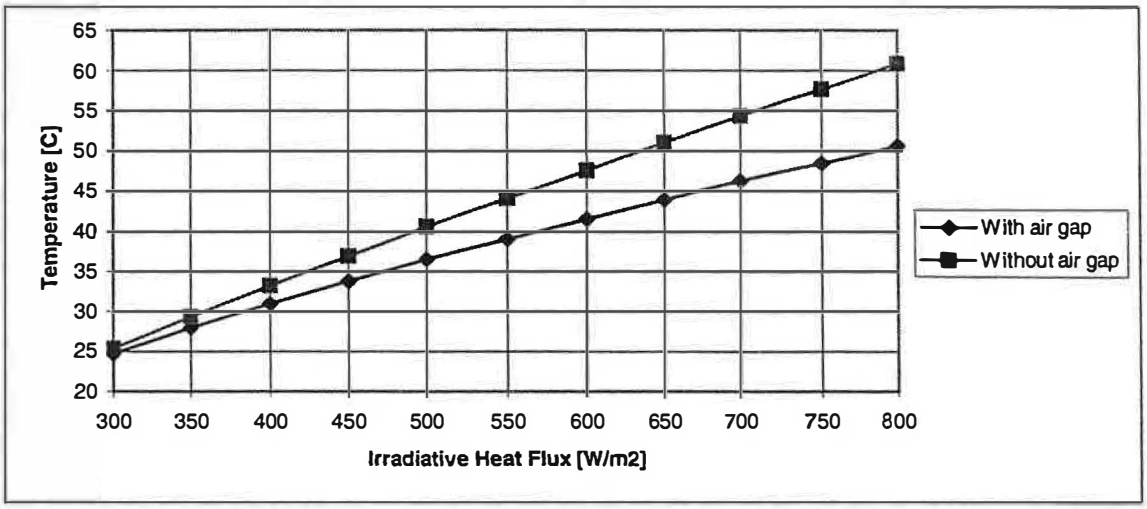

Figure 10 Comparison of cell temperature. (Valentino T (1999))

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