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RADIATIVE AND CONVECTIVE EFFECTS INSIDE GREENHOUSES

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Abstract. *This paper reports new results on the investigation being conducted on heating conditions inside greenhouses in close to real situations. In previous report, the pure Radiative transfer in presence of transparent and semi-transparent gases were studied. An optimization study was made to obtain the optimum tube sizing and location to attain certain restrictions. As the real problem involves Convective and Radiation Heat Transfer in presence of participating gases, a complex situation that precludes closed form solutions, the results presented herein were obtained using a Computational Package, FLUENT, available at the Mechanical Engineering Department of PUC-Rio. Results indicate clearly that the influence of both Radiation and Convection are important even at the relatively low temperatures involved and no simulation can be physically sound unless both effects are considered at the same time. However, the same complexity makes each simulation quite time consuming. The preliminary results to be shown may be used mainly for qualitative information but display interesting characteristics of the fluid and heat transfer inside greenhouses. A more lengthful study is still under way. Next steps in this investigation are also discussed.*

Keywords*. Greenhouse Simulation, Thermal Radiation, Convective Heat Transfer, Numerical Simulation*

1. Introduction

Due to the ever increasing environmental restrictions, more efficiency analyses on thermo-mechanical systems are being necessary. In many cases, however, the complexities of the physical reality are tremendous and only matemathically simple models were available until recently. In the past, most of these studies dealt mainly with conductive-convective systems, neglecting thermal radiation for many different reasons. However, experience indicates (Siegel and Howell, 2002) that radiative heat fluxes are often of the same order as natural convection fluxes, even at mild temperatures. Neglecting it sometimes over-simplify the solution but reduces its validity. Due to modern engineering technology and the long known fact that thermal efficiency increases with temperature, more sophisticated analysis of such situations are becoming gradually necessary.

Greenhouse thermal design is one of the many areas in which radiative coupled to convective heat transfer is relevant. In this situation, hot-water circulating tubes are used to keep the crop at the desired temperature level and produce the needed heating. Teitel & Tanny (1998) analyzed a very simple model and concluded that the heating pipes should be installed as close as possible to the crop. Unfortunately, many simplifications were introduced on their investigation. For instance, their study neglected the radiation blocking coming from the crops, ground and ceiling toward the pipes and other surfaces (resulting on a very stringent criteria for tube sizing), the likely solar heating occurring mostly over one of the surfaces, the influence of gas participation on the Radiation heat transfer, and most important, the Convective heat transfer. Recently, the present authors developed a more realist study that removed some of those restrictions and investigated how to increase greenhouse efficiency using adequate tube sizing and its location inside the cavity (Bastos & Braga, 2004). In that paper, mainly pure Radiative Heat Transfer was considered with only a few glimpses on the Convective Effects. From the literature, only the work developed by Vollebregt & Braak (1995) that modelled the internal greenhouse radiative and convective flows was found. However, the internal heating configuration (bank of 5 vertical tubes) used in their study was quite different from the one used by Teitel & Tanny (1998) and their results could not be used for comparison. This paper addresses the combined Radiation + (laminar and turbulent) Natural Convection heating inside greenhouses. The main objective of the present paper is to present preliminary results of the interactions between Radiative and Convective Heat Transfer. After a thorough study of such effects is completed, a necessary optimization analysis will be conducted to further understand how greenhouses efficency may be enhanced, considering not only the cost of the fuel needed to heat the ambient as well as the maximum heat fluxes that the crop may take to avoid surface burning.

2. Physical Model

The physical model is essentially the one previously studied. Its description is included here for completeness. Consider a rectangular greenhouse such as the one displayed on Fig. 1. The aspect ratio L_2 / L_1 may shift from 1 (for roses) to 5 (for tomatoes). Both cases were analyzed but only the results obtained for large aspect ratios are reported herein. At this stage, the enclosure is considered to be infinitely long in its third dimension. Surfaces 2 (left) and 4 (right) simulate the crop. The heating pipe, of diameter D, is located at a position defined as (x, y). Depending on the specific case to be considered later on, some or all of such variables are to be estimated following the current analysis.

All surfaces were modelled as black bodies as done by Teitel & Tanny (1998), although this is not a critical issue concerning numerical simulations. The lack of good spectral data on the crop emissivity turns this to be a not important feature. As it is known from the literature (e.g. Siegel and Howell, 2002), the emissivities for nonconductors are usually higher than for conductors and are affected differently from the orientation of the incident radiation. The temperatures chosen are T_1 = 293 K = T_2 = T_4 and T_3 (the ambient) = 283 K, is the lowest temperature in the cavity. The tube temperature is one of the parameters. For simplicity, in the present work, surface 3 indicates a panel, although it could be modified to be a virtual surface, such as an opening.

As it is well known, both the radiative and the convective heat transfer depend on physical parameters such as the temperatures, the thermal properties, but also on the geometry. Hot fluid (water, for instance) being pumped throughout the tube heats the greenhouse walls and the crops directly by Radiation and indirectly by Convection. It is desired that the crops are able to absorb energy uniformly along its (vertical) length, even considering that it looses heat to the upper horizontal surface near the top of the cavity.

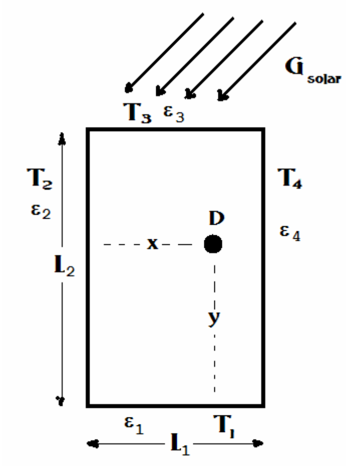


Figure 1. Greenhouse Geometry

Due to the relatively large temperature differences analysed, the turbulent natural convection flow was simulated through the use of the k-epsilon model with enhanced wall treatment. The Rayleigh number was defined accordingly to Eq. 1:

$$\mathbf{Ra} = \frac{\mathbf{g\beta\Delta T D^3}}{\alpha\nu} \tag{1}$$

Observing that the main objective of a greenhouse cavity is to heat the crops to allow their growth, a thermal efficiency may be defined as Eq. 2:

$$\eta = \frac{\mathbf{Q_2 + Q_4}}{\mathbf{Q_{tube}}} \tag{2}$$

3. Numerical Data

Energy transfer between surfaces is significantly altered in presence of semi transparent medium, due to absorption, emission and scattering of radiation (Siegel & Howell, 2002). Due to non homogeneous air condition inside greenhouses, resulting from the mixture of the generally called greenhouse gases, powder, small particles, leaves and others, it was decided to investigate how the heat transfer characteristics inside the greenhouse cavity would be affected by changes in the radiation intensity in the medium. For simplicity, a non-scattering medium was considered, although this will be eventually corrected. The results were obtained considering the absorption coefficient for the gas could be up to 0.5 but only results with this value will be presented. Due to the objectives of the present investigation, it was decided to use a specialized CFD package named FLUENT, available at the Mechanical Engineering Department of PUC-Rio, to solve the Radiative Transfer and the Convection Heat Transfer equations (Navier-Stokes and energy equations). The solution of the RT Equation was obtained through the use of the method of discrete ordinates, MDO, mainly because it handles both the the translucent medium and the transparent medium case, in which an analytical solution was available, as discussed by Bastos & Braga (2004), allowing assessment and numerical error control.

In essence, MDO substitute the Radiative Transfer Equation by a set of equations for an intensity of radiation angularly averaged over a finite number of ordinate directions (e.g. Modest, 1993). Integrals over a range of angles are replaced by sums over those ordinate directions. The results to be shown were obtained considering a total of 576 directions (12 theta divisions times 12 Phi divisions times 4, due to symmetry), a number sufficiently large to give results close to the analytical ones for the case of transparent media, matching engineering level of accuracy and sufficiently small to avoid the burden of large cost (or time) of computation. The triangular mesh used for the present simulations (due to the presence of the tube) handled 150 points along the vertical walls, 30 points along the horizontal walls and 20 points along the tube surface. Details of the accuracy results will be available elsewhere. Typical convergence criteria are shown in Table 1. In order to test the reliability of the simulation model, two simple problems (a pure radiative problem and a pure convective problem) were simulated and their solution compared with known analytical solution, whenever possible, and with those from the literature.

Table 1. Convergence Criteria

x velocity Equation: 1E-5	K Equation: 1E-5
y velocity Equation: 1E-5	ε Equation: 1E-5
Continuity Equation: 1E-3	Energy Equation: 1E-08
	Discrete Ordinate Equation: 1E-08

4. Results

Although the current investigation is not finished, as already mentioned, several interesting results have already been obtained and are presented herein. The main conclusion is that for a thorough study on Natural Convection flows, it is imperative to investigate Radiation Transfer at the same time. Here, our considerations will be concentraded on their implications towards the crop. The results shown here are all related to steady convergent solutions. A few cases in which apparently non physical symmetry were also obtained but these are not shown at this time. Among other features, it was decided to investigate the possibility of modeling the tube as a localized source, a simplification that could reduce drastically the computational effort. In what follows, results for three different simulations will be presented and discussed thoroughly in order to show the Physics envolved. After that, the investigation being undertaken will be discussed.

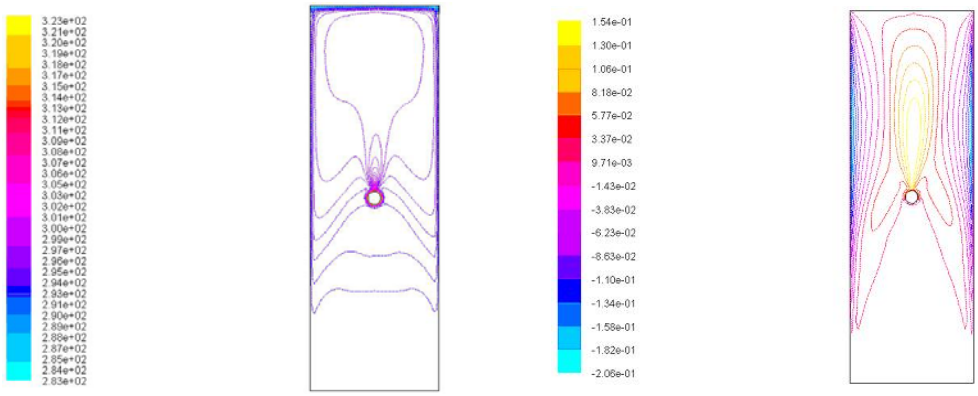
4.1 First Set of Data – One Tube

Table 2 below gives the data for the first steady state simulation (transient solutions were also obtained but those are not important in practical greenhouse situations). The iterative procedure is quite time consuming, as one may understand, but convergence was always achieved at all Rayleigh numbers studied. Graphical displays for the temperature and the vertical velocity profiles at a Rayleigh number equal to $2x10^6$ are given on Fig. 2, for the pure turbulent Natural Convection heat transfer situation, on Fig. 3, for the pure Radiative heat transfer situation (in this case, of course, the Rayleigh number has no meaning but one may consider the due temperature difference between tube and vertical walls) and on Fig. 4, for the combined Radiative + turbulent Natural Convection heat transfer. As it may be seen, the profiles are remarkably different.

Table 2. Data for the First Study. One tube

$T_1 = T_2 = T_4 = 293K$	$L_2 / L_1 = 3$
$T_3 = 283K$	x = 0,5 m / y = 1,5 m / r = 0,05 m
$T_{tube} = 323K$	$Ra = 2 \times 10^6$

Consider initially the pure Convective situation. Due to the chosen wall temperatures, the region below the tube is relatively calm, as indicated by the velocity profile. In consequence, the heat transfer there occurs mainly by conduction between walls and air and the isotherms below the tube are relatively horizontal, an indication of the cooling effect from the bottom. This situation is quite similar to the one studied by Braga & Vest (1987). Naturally, closest to the vertical walls, boundary effects are dominant. Due to the presence of the tube, two (relatively) small recirculation zones appear along each side of the vertical walls that represent the crop. The appearance of similar recirculation zones was also noticed by Mangiavacci (1988), and it was understood as indication of the effects of the obstacle along the path of the flow. Having in mind the greenhouse´s objectives, this non uniform heat transfer along the crop, clearly indicated in Fig. 5, is not a desired effect as it causes non-uniformities in the heat transfer distribution along the crops, therefore causing non uniform growth.



Figs. 2a and 2b Temperature and y-velocities for Case Study 1
Convective Heat Transfer Rayleigh number = 2 x 10^{-6}

For the pure radiative model, the temperature profile symmetry close to the tube is clearly indicated. It must be observed that without the gas participation, no isothermals would be seen at all (transparent gas situation). As the gravity was turned off, to model the pure radiative situation, no velocity profile is obtained. As before, heat transfer at the bottom of the cavity is not significant for the situation studied.

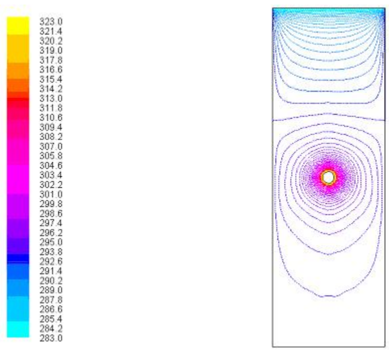
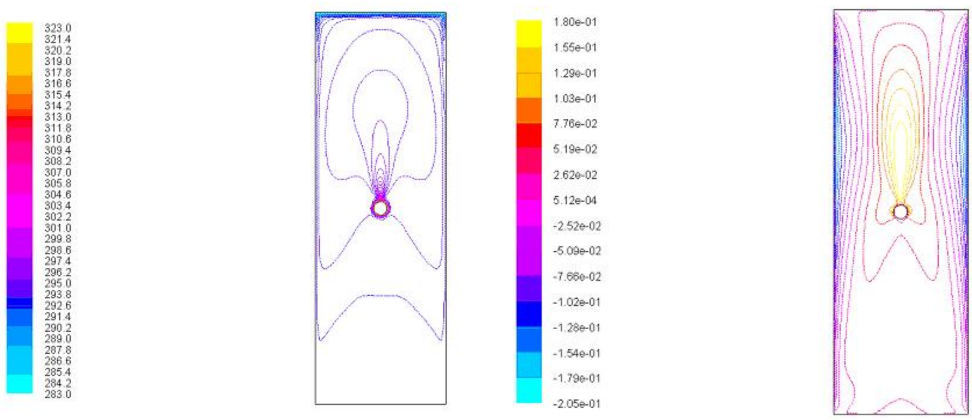


Fig. 3 Temperature Lines for Case Study 1: Pure Radiation Heat Transfer

Finally, the combined effect is observed in Fig. 4. The vertical symmetry is clearly seen. As before, the region below the tube is still calm. The boundary layers and the recirculating zones along the vertical walls are again clearly displayed.



Figs. 4a and 4b Temperature Lines for Case Study 1
Convection + Radiation Heat Transfer Rayleigh number = 2 x 10^6

Figure 5 indicates the heat flux along the wall (i.e. the crop). At the bottom of the greenhouse (y = 0), the heat transfer is quite small and stays roughly that way along the surface, due to the thermal boundary conditions at that region. Closest to the tube position, the local total (i.e. radiative + convective) heat transfer is significantly enhanced due to its presence. Noticing that the tube surface is hotter than the wall, this is a negative number, indicating that energy leaves the cavity (in real situation, this indicates that the crop is receiving energy). With a further increase in the y-direction, the directon of the heat transfer turns back towards the fluid inside the cavity and towards the top surface, the coolest one in the greenhouse. Therefore, greenhouses with large aspect ratio need a vertical sequence of tubes, as indicated by Vollebregt & Braak (1995) in opposition to what was studied by Teitel & Tanny (1998) and Bastos & Braga (2004). However, Vollebregt & Braak localized the bank of tubes in the lower part of the cavity. According to the results obtained in the present study, this is definitely not a good solution as it will maintain (and perhaps even intensify) the heat transfer non uniformity as no heating will occur in the upper region of the crop. The solution seems to involve an optimization study.

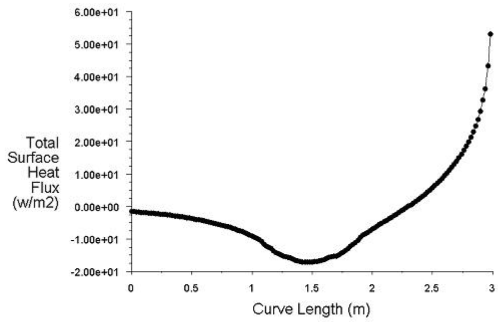


Fig. 5 Total Surface Heat Flux [W/m^2].
Combined Radiation + Convection Heat Transfer, Ra = 2 x 10^6

It is also important to analyse the heat transfer flux variaton along the tube surface. Figure 6.a, b, c and d indicate the results. The first case indicates the pure Convective heat transfer. The strong dip in this heat transfer at a position 0,075 m is an interesting result. Accordingly to the Fluent´s manual, the starting point of this plot is the point (0,55 m; 1,5 m), that is, the position at the tube closest to the right crop. From that, marching counter-clockwisely, the other positions at the plot are obtained sequentially. In consequence, the position of the dip is the one at 90^o to the left, that is, the highest position of the tube surface located at the centerline of the tube and the cavity. Due to the cavity symmetry, that is a location in which the fluid flow is quite slow and the local convective heat transfer coefficient is small. Therefore, at such location, heat transfer occurs mainly by Radiation and that is at its maximum value, due to the thermal boundary condition at the upper horizontal surface. Figure 6.b indicates the velocity profile at a horizontal plane above the tube. As clearly indicated, the upward flow, due to buoyancy, is significantly increased nearby the tube.

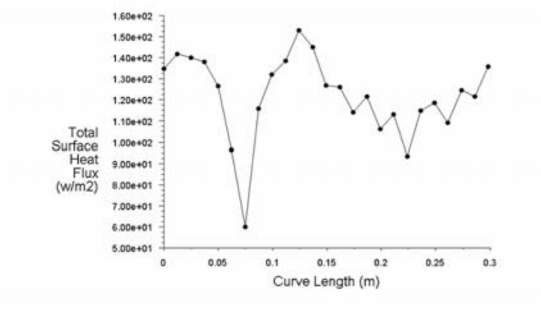


Fig 6a . Total Surface Heat Flux [W/m^2] along the tube.
a. Pure Convective Heat Transfer

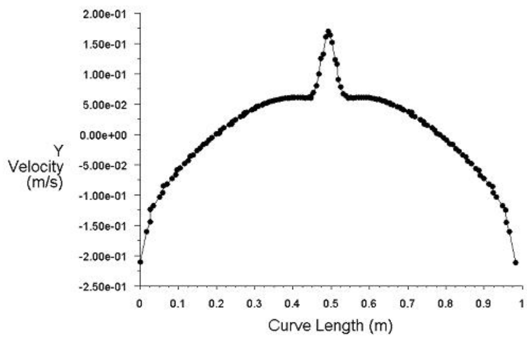


Fig. 6b. Velocity Profile at a horizontal plane above the tube.

For the pure Radiative situation, relatively strong heat transfer occurs at the upper tube surface, but not at the bottom due to the specified temperature boundary conditions (indicated on Table 2 above). Heating in this lower region is due mainly to the participating medium. For the combined physical situation, the heat flux profile at the tube wall surface is clearly the resulting from both effects. Due to the participant gas, the overall results are not the sum of each effect. Table 3 displays the overall heat transfer from each surface for the three cases studied. These results confirm the analysis done.

For the particular situation shown in this first case, neglecting Radiation implies on considerable smaller heat transfer from the tube (by 36%) and neglecting Convection reduces it by 63%. Therefore, both effects should be included in any careful analysis. It may be seen that the "real" (in the sense that most thermal effects are considered) greenhouse efficiency for the present case is only 17%, instead of 32%, if pure convection is considered, a quite often situation in Natural Convection flows. This means that most of the energy put away through the tube does not reach the crops as it is used to pump air through the cavity. As indicated in Fig. 5, this is not so in the crop region around the tube.

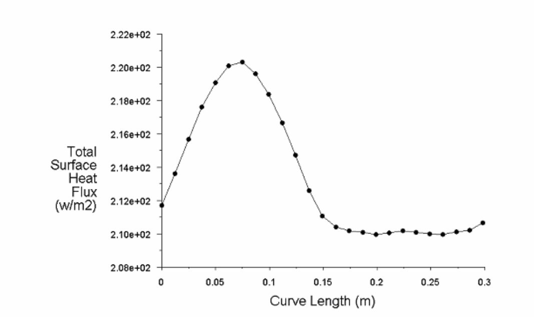


Fig 6c. Total Surface Heat Flux [W/m^2] along the tube.
Pure Radiative Heat Transfer

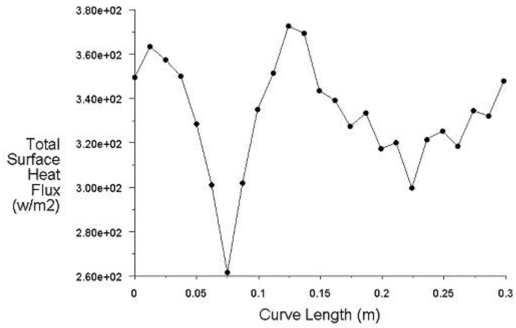


Fig 6d. Total Surface Heat Flux [W/m^2] along the tube.
Combined Convective and Radiative Heat Transfer

Table 3. Total Heat Transfer, One Tube, Ra = 2 x 10^6

Heat Transfer [W]	Pure Radiation	Pure Convection	Radiation + Convection
Q_2	-4.5	-6.0	-8.8
Q_4	-4.5	-6.2	-8.9
Q_1	-2.8	-0.00	-2.6
Q_3	-55.2	-26.1	-83.7
Q_{tube}	66.8	38.2	104.1
Efficiency	13,5%	31,9%	17,0%

4.2 Second Set of Data – One Tube

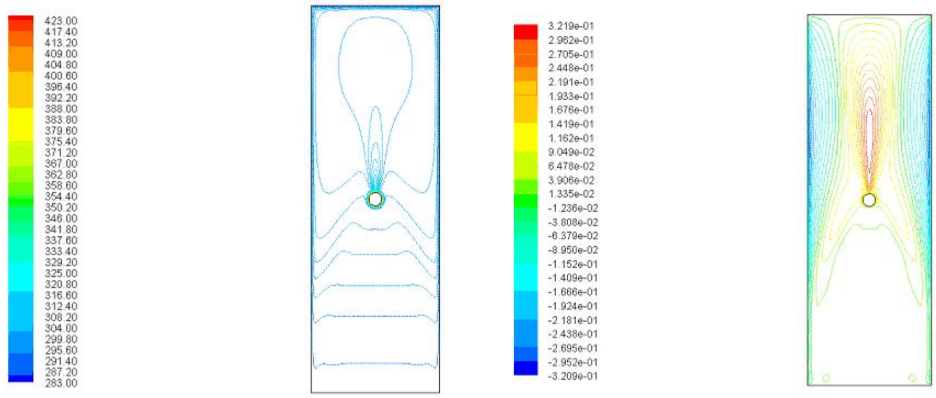
Next, the results for a higher tube temperature for the combined Radiative and Turbulent Natural Convection Heat Transfer situation are indicated (other cases are omitted due to space limitations). The boundary conditions are displayed in Table 4.

Table 4. Data for the First Study. One tube

$T_1 = T_2 = T_4 = 293$ K	$L_2 / L_1 = 3$
$T_3 = 283$ K	x = 0,5 m / y = 1,5 m / r = 0,05 m
$T_{tube} = 423$ K	Ra = 7,3 x 10^6

As it may be seen, the thermal effects and the velocity profile are much more intense than in the previous case. However, the general aspect is roughly similar to the previous.

As indicated in Table 4, heat transfer rates are also much higher, as one should expect. In this case, the thermal efficiency increases from the previous situation.



Figs. 6a and 6b Temperature Lines for Case Study 2
Convection + Radiation Heat Transfer Rayleigh number = 7,3 x 10^6

Table 4. Total Heat Transfer, One Tube, Ra = 7,3 x 10^6

	Radiation + Convection
Q_2	-220.9 W
Q_4	-220.9 W
Q_1	-26.7 W
Q_3	-160.0 W
Q_{tube}	628.5 W
Efficiency	70,3%

4.3 Third Set of Data – Two Tubes

As used by Teitel & Tanny (1998), for instance, quite often two horizontal tubes are used inside greenhouses, each one as closest as possible to the vertical crop. However, as investigated by Bernardo & Braga (2004), this is not recommended as it may result on crop burning, a non-desired effect. At least in theory, it should be wise to maintain some distance from both lateral walls. In the present study, no attempt was made to optimize tube sizing and location as this is a quite demanding task due to the physics of the problem that, as already mentioned, precludes any analytical solution. In any event, some simulations of the combined Radiative and Convective Heat Transfer in presence of the two tubes were made and a few results are shown herein for completeness. The results were obtained for a Rayleigh number = 3,2 x 10^7, aspect ratio = $L_2 / L_1 = 5$, D = 0,2 m.

As indicated in Figs. 7a and 7b, the effects are quite different from those previously shown although a similar stagnant heat conduction region occurs in the lower part of the greenhouse cavity and a similar non uniform crop heating occurs.

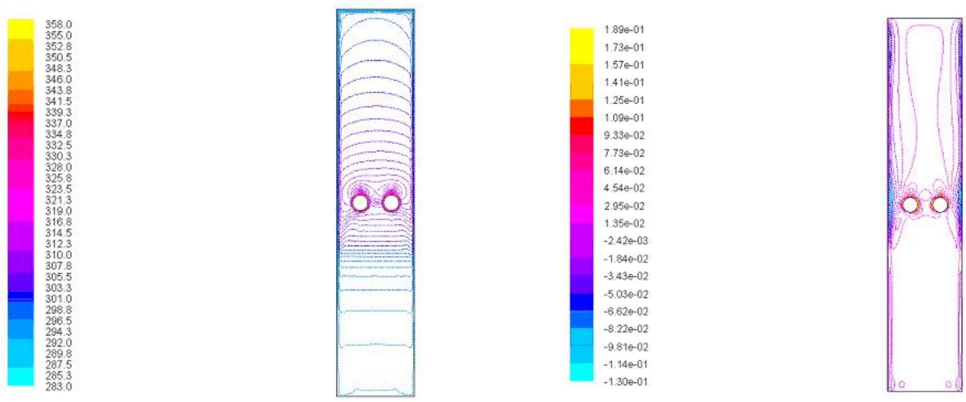


Fig 7 a and b. Temperature and y-velocities for Case Study 3
Combined Radiative and Convective Heat Transfer
Rayleigh number = 3,2 x 10^7

Table 6. Total Heat Fluxes at each wall in presence of two tubes

Q_2	-359.6 W
Q_4	-359.4 W
Q_1	-15.7 W
Q_3	-129.3 W
$Q_{left\ tube}$	432.0 W
$Q_{right\ tube}$	431.9 W
Efficiency	83.2%

5. Concluding Remarks

The present paper describes the work under development to better understand the heat transfer inside greenhouse thermal cavities used to grow crops. The most complete problem, introduced herein, involves Radiation in presence of a semi transparent gas and Natural Convection Heat Transfer, a situation that precluded so far a throughfull optimization analysis. In order to prepare for a more complete investigation, the study turned to the numerical CFD package, FLUENT, that allowed the analysis of a participant gas in presence of both Radiation, in presence of a translucent medium (air), and Turbulent Natural Convection. After an extensive numerical investigation on computational times, mesh sizes, convergent criterion, optimum number of directions for the Method of Discrete Ordinates and others, a good agreement between numerical and analytical results, whenever they were available, were obtained. After that, the investigation on the effects of the participant medium was conducted. The results so far obtained indicate that the combined model offers more realist results if compared to each individual heat transfer mode. Further investigation on these effects is still being conducted due to the intrinsic difficulties. It is hoped that the combined effects will render the simulation more efficient and enlighten the physics of the heat transfer mechanisms inside greenhouses. In future developments, it is desired to proceed with the optimization analysis introduced on a previous stage of the current investigation in order to enhance the effectiveness of greenhouse crops. As long as a single tube does not seem effective to induce uniform heating, a bank of tubes may be more efficient for this matter. However, its number, its diameter and certainly its location are still to be estimated.

6. Acknowledgement

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