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ENVIRONMENTAL FRIENDLY HIGH EFFICIENT LIGHT SOURCE

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RÉSUMÉ

For the year 2005, the present project was dedicated to study the feasibility of a microwave driven plasma lamp that meets the following characteristics:

1- No moving part: this is fully achieved. We have solved the problem of standing high temperature in the bulb without any forced cooling (fans). This innovation is not yet patented and thus cannot be described in the present document.

2- Luminous efficiency > 100 Lm/W. This goal is almost achieved. We have reached the performance of 86 Lm/W thanks to the innovation. This came out of the first tries; it seems thus fairly possible to improve the IS to reach higher efficiency.

3- Nominal power below 100 W. this goal is half-way achieved. The luminous efficiency of 86 Lm/W has been obtained at a consumption of 650 W, thus at half of the nominal power of the reference lamp SOLAR-1000, which has a rotating bulb. The key here is to reduce to size of the bulb.

It has been agreed to extend the stage of laboratory tests till mid 2006 for the three reasons:

1- Tries of small bulbs need a tuneable microwave system. This is a more complex set-up that has already been build and tested by the industrial partner and has just been moved to HEIG-VD.

2- It came out that three additional parameters should to be studied: two are related to the innovative system and the third is the bulb filling.

3- An investigation of the plasma stability is necessary before stepping into the design of a final prototype.

Goal of the project

Background

Lighting-related electricity production for the year 1997 was 2016 TWh. The corresponding carbon dioxide emissions were 1775 million tonnes. For the industrialized countries, national lighting electricity use ranges from 5 % to 15 %, while in developing countries the value can be as high as 86 % of the total electricity use [1].

More efficient use of lighting energy would limit the rate of increase of electricity consumption and the rate of construction of new power plans, and reduce the emissions of greenhouse gases and other pollutants.

Our research

We are working at the development of a very high efficient type of light source (target value: 140 lm/W) which provides colour rendering that meets the standard of buildings. Nowadays, most of the low-energy lamps on the market are of fluorescent type (80 Lm/W), although they contain mercury, a very harmful substance which is strictly regulated. Environmental friendly alternatives, based on sulphur vapour excited by microwaves, are in development in different countries (South-Korea, USA, Nederland, Russia and probably also in Germany). At high temperature, the vapour radiates a continuous spectrum that fits well to the human eye's sensitivity.

Our research in this field began thanks to the support of the University Of Applied Sciences Of Western Switzerland (HES-SO) by the project Nanosun Ph1 which was first dedicated to analyse the SOLAR-1000 lamp, the first commercialised sulphur lamp, a device of nominal input power of 1300 Watt. This device is fitted with a spinning bulb and uses a process discovered in 1995 by Ury et al. (patent [2]). We intend to improve the technology by suppressing this motion and by replacing the cathode of the magnetron by a cold cathode made of Nanotubes (longer life time, higher efficiency). Our measures have shown that the rotation of the bulb does not only cool down the bulb, and therefore avoid melting at full power, but also increases the luminous efficiency obtained at a given power: at 500 Watts (consumption of the magnetron), the efficiency of the SOLAR-1000 lamp goes up form 50 to 100 Lumen/Watt when the bulb is put into rotation at full speed (Figure 6). Besides, we have checked that the energetic cost of rotating the bulb is insignificant in regard to the consumption of the magnetron.

Goal of the present project

This project is dedicated to the reduction of the nominal power and the renouncement of any mobile mechanism but keeping the efficiency at a high level. This progress will allow matching a larger market segment, in addition to extending the life time of the lamp and reducing drastically its cost of fabrication. These three points should mature the technology up to profit-earning state.

For the year 2005, the present project was dedicated to study the feasibility of a lamp that meets the following characteristics:

1- **No moving part**. Forced cooled lamps are not adapted to lighting in buildings because moving mechanical components penalise heavily the reliability or the cost of the lamp.

2- **Luminous efficiency > 100 Lm/W**. The idea is to surpass fluorescent lamps (~80 Lm/W); these lose 50% of performance during their life. Electrodes less lamps experience much less aging. The lamp we are developing has no electrodes. Moreover, fitted with a cold cathode magnetron it should reach outstanding lifetimes.

3- **Nominal power below 100 W**. This allows tackling the largest segment of market.

Work done and reached results

The planning as it was at the proposal stage is shown on Figure 1 [3]. The four first steps, of which the three first are specific to the preset project, have been achieved. A summary of the main results is given hereafter.

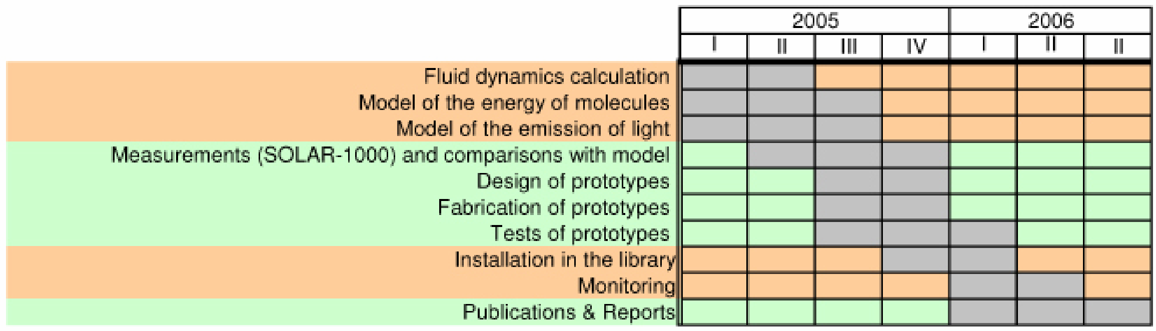

Figure 1: Lines in red are specific work of the present project; those in green are common with the HES-SO project (Nanosun PH1)

Fluid dynamics analyse

Two approaches have been leaded in parallel: analytical modelling on one hand and fluid dynamics calculations (CFD) on the other. Both of them are set in a rotary referential attached to the bulb. Among different intermediate results, the analytical approach showed first that the terrestrial gravitation is globally negligible in regard to the centrifugal force and that the distribution of temperature generates a distribution of density that makes the field of force irrotational; thus the force cannot be balanced by a gradient of pressure everywhere in the bulb and as a result it gives rise to a motion of convection inside the bulb. The driving force is the difference of centrifugal force between the hot centre and cold periphery (red and blue zones on Figure 2).

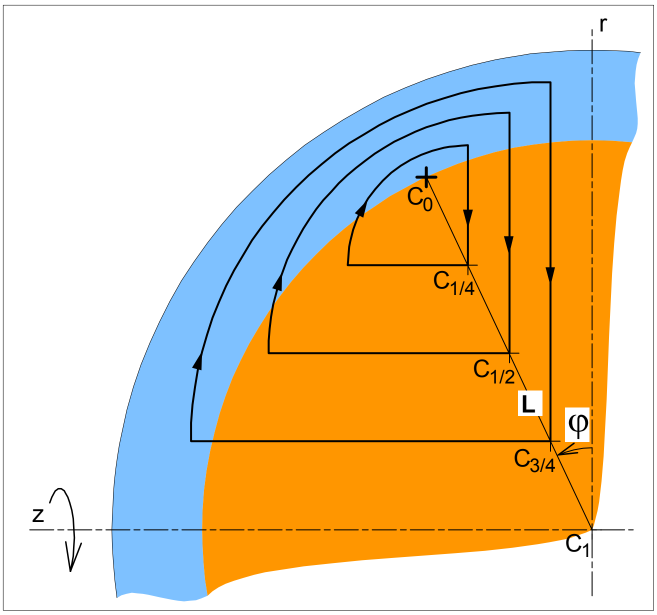

Figure 2: Simplified streamlines (analytical approach). In red: hot zone (low density); in blue: cold zone (high density)

The second approach has proceeded in running the CFD code *Fluent*®, version 6.2.16, for spherical temperature distributions corresponding to thermal injected powers of 500, 750 and 1000 W (microwave inflow). Convective heat transfer from the bulb walls to the ambient has been considered in the calculation. The simulations provided visualisations of the convective flow patterns.

Furthermore streamlines have been assessed by tracking particles. The results confirm the pattern of streamlines that has been figure out in the analytical approach [4, 5]; the flow forms indeed two vortexes in mirror symmetry to the equatorial plan (Figure 2 and Figure 3). But the actual kinetic of the thermal convection is not assessed by the present CFD calculation. First, because it does not take into account the bulk viscosity as this is here the main source of dissipation of mechanical energy, and second, because dissociation is neither taken into account although it is a strong driving force as it has a large impact on density.

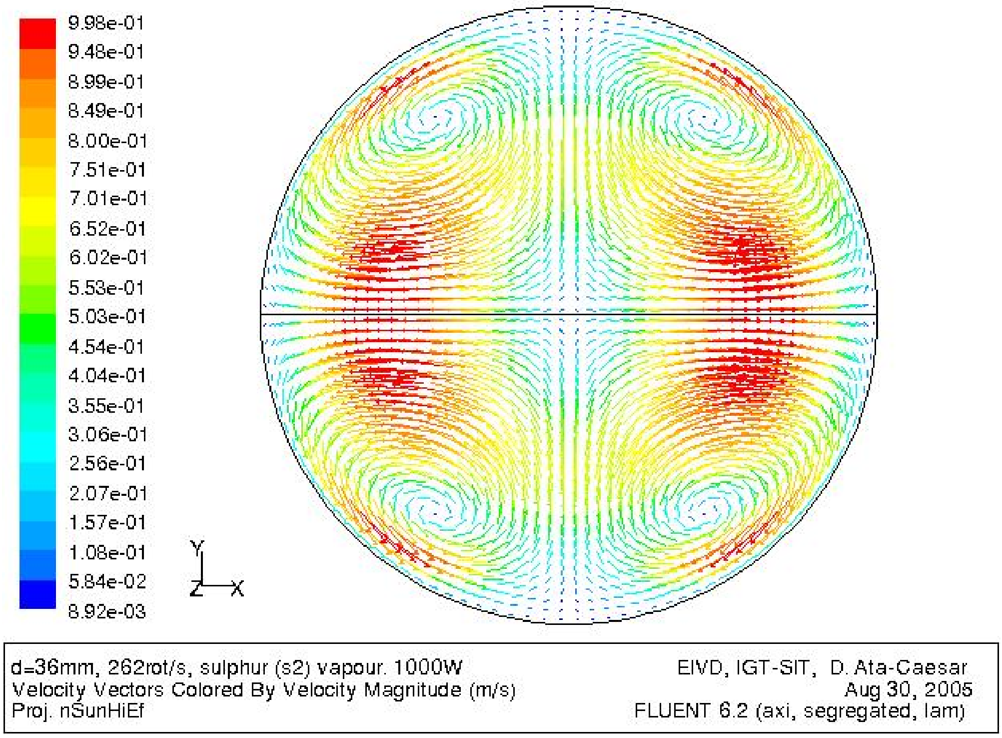

Figure 3: Field of speed in a referential attached to the bulb (CFD Result)

From those two approaches we see that a thermal convection (macroscopic motion) moves the molecule out from the hot centre to the cold periphery and back again into the core of the plasma, like the thermal diffusion does (microscopic motion), but in an ordered way. Our model of this thermal convection is of course quite schematic since the temperature distribution should be coupled to the mass flow. This model shows nevertheless that, in add to the thermal oscillations due to thermal diffusion, the molecules are submitted to large thermal cycles. The magnitude order of the temperature in the bulb is in agreement with the model of Johnston [6]. The plasma is hot enough to dissociate a significant part of the sulphur vapour [7]. Furthermore the simulations confirm that its temperature is an increasing function of the injected power. As we will see later, this implies that a reduction of the power must be balanced by a sizing down of the bulb in order to avoid a lowering of the luminous efficiency.

The entropy production changes certainly if the bulb is rotating or not. On one hand thermal convection produces entropy (cycles of molecular dissociation and recombination and of dilatation and compression). On the other diffusion is also a source of entropy. It is an increasing function of temperature gradient but a decreasing function of thermal convection. Prigogine has shown indeed that this macroscopic motion can be considered as a dissipative structure: a system loses entropy whenever thermal convection develops inside in comparison to the case where all the energy is thermal (microscopic motion). The corresponding loos are in the order of the ratio of the kinetic energy of thermal convection to the mean temperature in the system [8]:

$$\Delta S \approx -E_{Cin} / \overline{T} \qquad \text{Équation 1}$$

According to Prigogine's principle, a state of non-equilibrium in fixed thermal conditions becomes also steady once the production of entropy in the system has reached its minimum. If the system is closed moreover, the income of entropy cannot grow while the thermal boundary conditions are set [8]. The steadiness is then reached when the entropy of the system is minimal for the given thermal boundary conditions. In our application, the Équation 1 implies that the convection will set in such a steady regime that its kinetics energy is maximal. This gives us a mean to position the centres of the two symmetrical vortexes (parameters L and φ).

$$\partial_L E_{Cin} = \partial_\varphi E_{Cin} = 0 \qquad \text{Équation 2}$$

There are in the bulb only two processes that dissipate mechanical energy: the viscous friction and the dilatation and compression, but the second is largely dominant (the shear viscosity lays around 50 $\mu Pa \cdot s$ as the bulb viscosity is in the range of 1 $Pa \cdot s$). Consequently, at steady state the rate of work of the centrifuge force equals the loos due to dilatation and compression, whose density is simply the bulk viscosity times the square of the divergence of the speed. This balance allows assessing the mean speed of each streamlines and thus leads to the total kinetic energy of thermal convection. The parametric study shows that this quantity passes by a maximum (Figure 4) as foresees the theory of Prigogine.

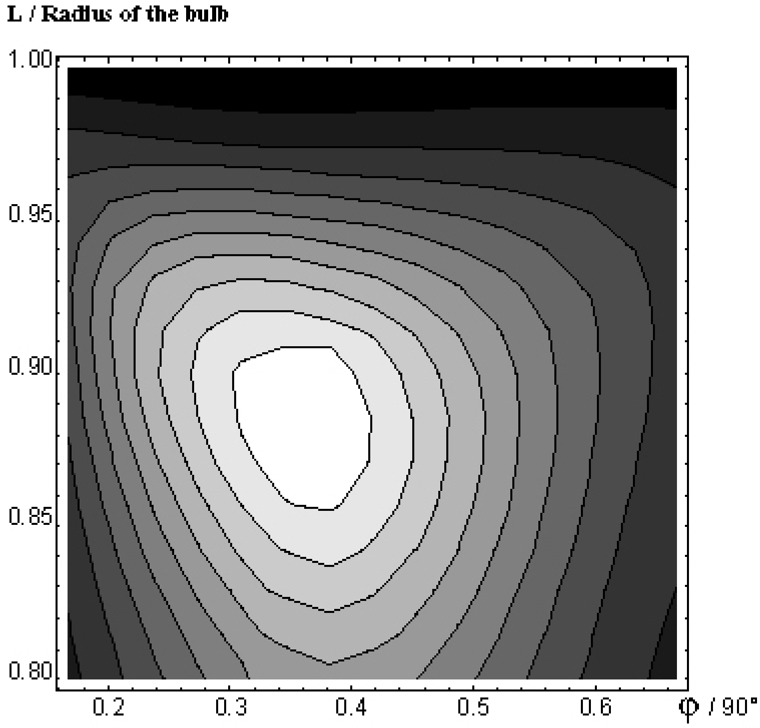

Figure 4: Kinetic energy of thermal convection versus the position of the centres of the two symmetrical vortexes (see Figure 2).

Model of the energy of molecules and of the emission of light

As long as we maintain the input flow of microwave, the bulb filling stays out of thermodynamic equilibrium with the environment since its pressure and temperature don't come back to their starting value, in opposite to the situation at rest, for which the thermodynamic equilibrium is established. The plasma stays at high temperature by dissipating the electromagnetic energy carried by the microwaves it absorbs. This process outputs only heat.

A flux of thermal energy can however produce work; this is what a heat engine does. In stationary regime, all the electromagnetic energy dissipated inside the bulb is transferred to its outside, but not solely as heat. Indeed, the emission of the lamp is not only due to thermal radiation as its spectrum does not obey Planck's law (Figure 5). Infrared monitoring makes this clear. This measures the temperature at which a black body would provides the same radiations in a given infrared frequency band. At 800 W for instance (supplied power), this temperature lays around 600°C when the bulb turns at normal speed (3'000 tr/mn) [9]. But at such a temperature, the thermal emission in the visible (410 - 780 nm) is extremely low and the luminous efficiency of such a radiation is insignificant (~ 0.2 Lm/W).

The origin of the optical emission of sulphur (from 300 to 900 nm, Figure 5) has been identified 25 years ago [10]. The photons are produced at the relaxation of diatomic molecules from a certain excited electronic state to the ground electronic state, a reversible process (photo-absorption). Being not due to thermal radiation, this part of the emission must be considered as a production of work, in the sense of thermodynamics, as the resting part is a flux of heat.

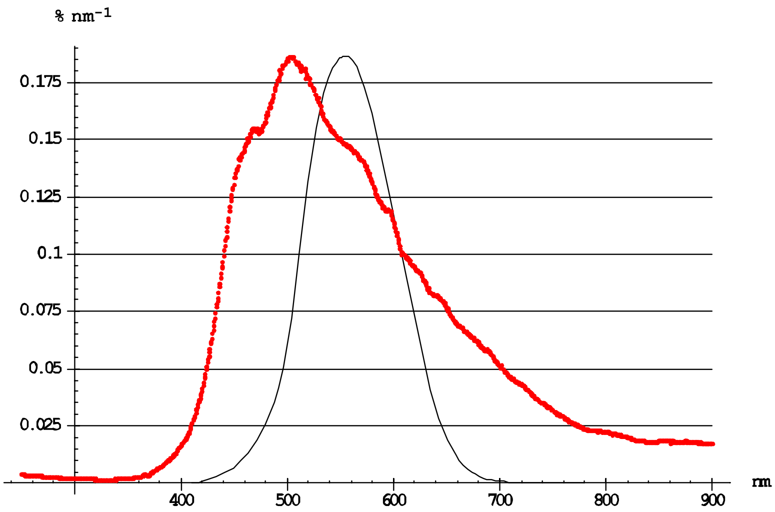

Figure 5: Ratio of the emission of sulphur to the magnetron supply (529 W), bulb in rotation. The thin line shows the relative eye sensitivity. Luminous efficiency = 103 Lm/W.

Let's consider in first step a small volume of space whose temperature can be said uniform (T). This is an opened system; its intern energy could vary only by:

- Exchanging mass with the outside (dE_{Ext}),
- Exchanging heat with the outside ($T \cdot dS_{Ext}$),
- Exchanging work with the outside (non thermal radiation dW),
- Producing entropy ($T \cdot dS_{Int} > 0$); this results out from the irreversible intern processes (dissociation and recombination of molecules, dilatation and compression, friction…).

This leads us to the following relation:

$$dE = T \cdot d\left(S_{Ext} + S_{Int}\right) + dW + dE_{Ext} \qquad \text{Équation 3}$$

Let's simplify the convection inside the bulb to a schema of two volumes; a central one of very high temperature T_H (in red on Figure 2), and a peripheral one of lower temperature T_L (in blue). During a short interval of time, the energy in the hotter volume may vary according to the Équation 3 by $\Delta E_H = T_H \cdot \left(\Delta S_H + \Delta S_{IntH}\right) + \Delta W_H + \Delta E_{ExtH}$, and in the volume of milder temperature by $\Delta E_L = -T_L \cdot \left(\Delta S_H + \Delta S_{IntH} + \Delta S_{IntL}\right) + \Delta W_L + \Delta E_{ExtL}$.

Let's now count the exchanges that occur during this interval of time. In stationary regime, the mass Δm that flows from the peripheral volume to the centre is the same than the one that flows back to the cooler outer layers given that the bulb is closed. The energy fluxes due to mass transfer between the two volumes are thus equal in magnitude but of opposite sign:

$$\Delta E_{ExtL} = \Delta m \cdot \left(c_{pH} \cdot T_H - c_{pL} \cdot T_L\right) = -\Delta E_{ExtH} \qquad \text{Équation 4}$$

At stationary regime, the energy inside the bulb is constant: $\Delta E_H + \Delta E_L = 0$. Thus:

$$T_H \cdot \left(\Delta S_H + \Delta S_{IntH}\right) + \Delta W_H - T_L \cdot \left(\Delta S_H + \Delta S_{IntH} + \Delta S_{IntL}\right) + \Delta W_L = 0 \qquad \text{Équation 5}$$

The terms of mass transfer ΔE_{ExtL} and ΔE_{ExtH} cancel out; this makes our model relevant for static bulbs a well as for spinning ones, but the hotter volume is delimited by the luminous zone (the plasma) in the case of a static bulb as it can be then completely decentred. Without rotation of the bulb, the thermal convection becomes much less important. But the thermal diffusion between the tempered periphery and the hot centre is still active and maybe enhanced. Besides the heat sink is then less good; thus the temperature in periphery T_L rises, but the temperature in the core T_H is probably not so much affected since the ability of sulphur vapour to dissipate microwaves increases with temperature, at least up to some extent. We have deduced this feature form observations of plasmas in static bulbs.

The net output of work is, in positive value:

$$\Delta W = -\left(\Delta W_H + \Delta W_L\right) = T_H \cdot \left(\Delta S_H + \Delta S_{IntH}\right) - T_L \cdot \left(\Delta S_H + \Delta S_{IntH} + \Delta S_{IntL}\right) \qquad \text{Équation 6}$$

The thermodynamic efficiency is by definition:

$$\eta = \frac{\Delta W}{\Delta Q} = \frac{\left(T_H - T_L\right) \cdot \Delta S_H - T_L \cdot \Delta S_{Int} + T_H \cdot \Delta S_{IntH}}{\Delta Q} \qquad \text{Équation 7}$$

where ΔS_{Int} is the total of entropy production $\Delta S_{Int} = \Delta S_{IntH} + \Delta S_{IntL}$.

ΔQ is the amount of heat brought by absorption of microwaves in the whole bulb. As said above, this absorption mechanism is enhanced at high temperature. Observations of static bulbs confirm that there is more absorption in the core of the plasma than anywhere else. We admit for that reason that $\Delta Q \cong T_H \cdot \Delta S_H$:

$$\eta \cong \frac{T_H - T_L}{T_H} - \frac{T_L \cdot \Delta S_{Int}}{\Delta Q} + \frac{\Delta S_{IntH}}{\Delta S_H} \qquad \text{Équation 8}$$

The plasma receives a large amount of heat (microwave) but in a well distributed manner; therefore the gradients are weak in this volume and consequently its production of entropy ΔS_{IntH} is certainly small in regards to the flux of entropy it receives ΔS_H ; dropping out the last term in Équation 8 should lead to a limited underestimation of the thermodynamic efficiency:

$$\eta \cong \frac{T_H - T_L}{T_H} - \frac{T_L \cdot \Delta S_{Int}}{\Delta Q} \qquad \text{Équation 9}$$

Effect of spinning the bulb

From Équation 9, we see that loos of entropy production enhance necessarily the efficiency of the system. Équation 1 gives thus a first argument for interpreting why rotating the bulb increases the luminous efficiency (Figure 6).

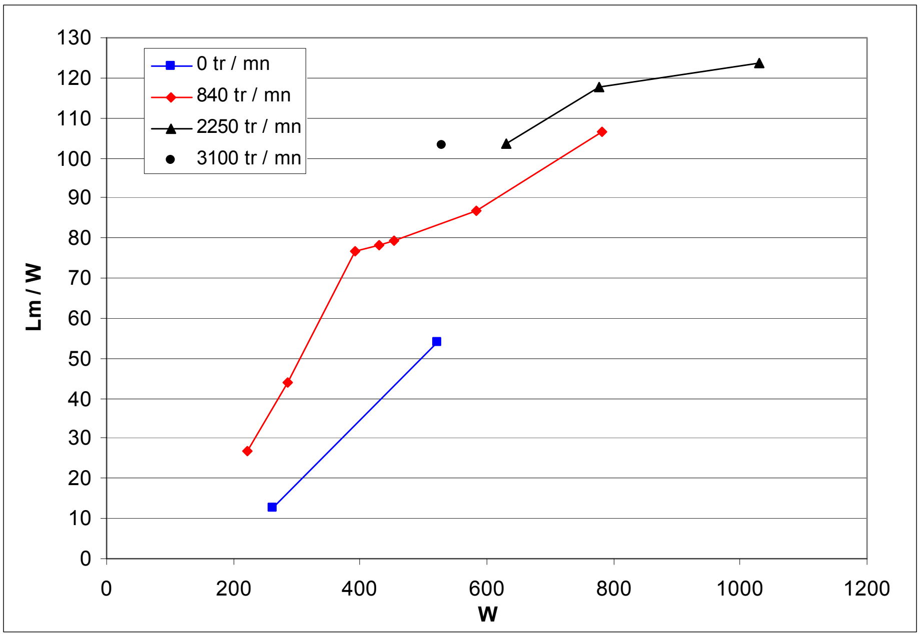

Figure 6: Luminous efficiency versus the power supplied to the magnetron; lamp SOLAR-1000, bulb spinning at different speeds.

The Équation 9 gives a global appraisal of the effect of spinning the bulb: as seen before, a better cooling of the bulb at given absorbed power ΔQ certainly pulls down the temperature outside the plasma T_L . This leaves more microwaves power for the plasma and thus avoids that T_H decreases as much as T_L . Importing those deductions into Équation 9, we see that rotating the bulb:

- enhances Carnot's efficiency: $(T_H - T_L)/T_H$
- reduce the efficiency loos of due to irreversible processes: $T_L \cdot \Delta S_{\text{int}} / \Delta Q$

Both actions contribute to improve the lamp (better thermodynamic efficiency and by consequence better luminous efficiency as well). This completes our explanation of the positive effect of spinning the bulb on the efficiency of the lamp.

Measurements on the SOLAR-1000 lamp at mid power and bulb in rotation (Figure 5) have shown that the thermodynamic efficiency η can reach 40%. Posing values of 3'000 K and 1'000 K for T_H and T_L respectively, we get 67% for Carnot's efficiency. This is logically above η since the difference $(T_H - T_L)/T_H - \eta \cong T_L \cdot \Delta S_{Int} / \Delta Q$ must be positive; otherwise the second principle of thermodynamics would be violated!

The Équation 9 opens on top an interpretation of the fact that the efficiencies, the thermodynamic one as well as the luminous one, are increasing functions of the electrical consumption, up to some limit avoiding at least the bulb fusion (made of fused quartz). This has been observed till 1000 W with the standard bulb in rotation and till a little above half of this power with different static bulbs. Indeed, the more microwave feed the bulb, the hotter is the plasma and the more energy it absorbs. But the temperature out of the plasma T_L is less affected since the microwave absorption coefficient is an increasing function of temperature. This makes clear that we obtain a similar effect on the efficiency as the one we obtained by improving the heat sink at constant supplied power (lowering T_L). This analyse points out also that it should be possible to reduce the power of the lamp without significant loos of efficiency by sizing down the bulb (higher pressure and by consequence hotter plasma) as long as no point of accumulation of heat appears on the inside surface of the bulb; the Innovative System (IS) seems to avoid this.

Beside this thermodynamic approach, we know that the optical emission is due to the relaxation of diatomic molecules from a certain excited electronic state down to the ground electronic state. The population of the excited state is renewed by recombination of dissociated molecules. The net rate of relaxation (relaxations minus excitations) is thus proportional to the degree of dissociation, which is an increasing function of temperature but depends also on other parameters. It becomes obvious that rising the degree of dissociation at given temperature would enhance the efficiency; that is what the IS does. But moreover, it shifts the emission towards longer wavelength, enhancing in this way the luminous efficiency. The performance of a static bulb has passed from 41 Lm/W to 86 Lm/W thanks to the IS (Figure 7). It becomes comparable to what spinning bulbs provide (Figure 5).

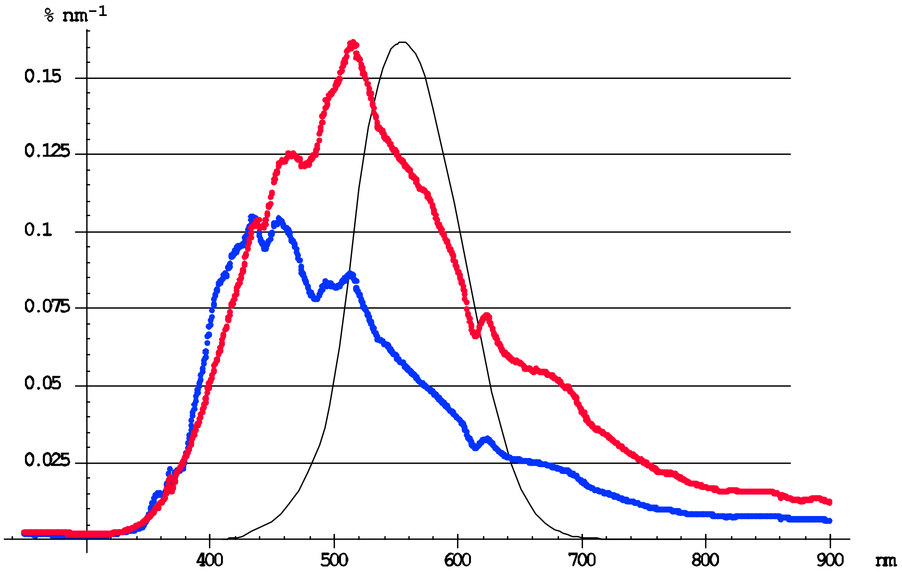

*Figure 7: Ratio of the emission of sulphur to the magnetron supply. **Static bulb**. Innovative System on (red line) and off (blue line). The thin line shows the relative eye sensitivity.*

National collaboration

The project could not have progress with out the important contribution of the company *Solaronix*. Here are the main numbers concerning their investments in the project for the present year:

Labour: 3 man-months	40'000.-
MW test bench	15'000.-
Innovative System	5'000.-
Bulbs filling incl. mat.	5'000.-
Magnetron & thermometry	3'000.-
Total:	68'000.-

Besides, collaboration with EPFL (Laboratory of Building Physics) has been settled. In particular we are grateful for advices and borrow of laboratory equipments (calibrated light source, photometers).

International collaboration

The non confidential part of the project has been presented at a meeting of the International Energy Agency, Annex 45 (Energy Efficient Electric Lighting for Buildings), in April 2005. Contacts have been taken for exchanging information.

Evaluation of the year 2005 and perspectives for 2006

For the year 2005, most of the goals have been reached:

1- No moving part. **This goal is fully achieved** [11]. We have solved the problem of standing high temperature in the bulb without any forced cooling (fans or rotation of the bulb). This Innovative System (IS) is not yet patented and thus cannot be described here.

2- Luminous efficiency > 100 Lm/W. This goal is almost achieved. We have reached the performance of **86 Lm/W** thanks to the IS (Figure 8) [11]. This came out of the first tries; it seems thus fairly possible to improve the IS to reach higher efficiency. Moreover, replacing the magnetron cathode by a cold one would increases this performance up to **91 Lm/W** [11]. This issue will be addressed through another project (HES-SO finances 6 months of engineer, additional 6 months required).

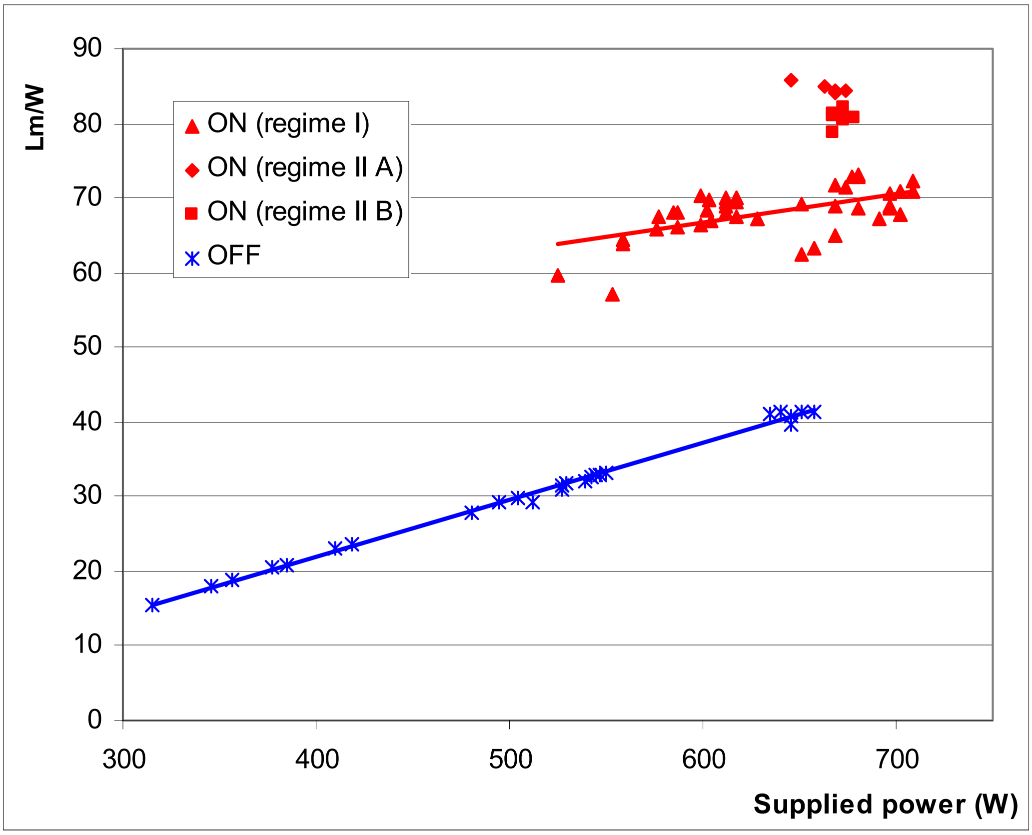

Figure 8: Efficiency of a static bulb filled with sulphur. Innovative System on (in red) and off (in blue)

3- Nominal power below 100 W. this goal is half-way achieved. The luminous efficiency of 86 Lm/W has been obtained at a consumption of **650 W**, thus at half of the nominal power of the SOLAR-1000 lamp (spinning bulb), which has a comparable efficiency at this power (Figure 6) [11]. The key here is to reduce to size of the bulb. Besides, the availability of low power magnetrons had been checked: RM118 model from *LG & Daewoo* outputs 100W with an efficiency of 64% (two units have been bought).

It has been however decided to prolong the stage of laboratory tests till mid 2006 for the three following reasons:

1- It has turned out impossible to test the small bulbs in the standard microwave set-up. The difficulty that arose comes from the ignition of the lamp. This proceeds in two steps. First a standing wave grows in the cavity till an electrical discharge appears in the bulb (it is filled with rare gas). Then the sulphur evaporates. Therefore, the ignition happens only if the quality factor of the cavity is high enough. Changing the bulb may change this characteristic. In this case, the modification of the microwave cavity must be compensated. This is the role of the tuner that is placed in the new set-up. We have also added a bidirectional microwave flux meter and a thermostatic regulation of the magnetron to measure the power it dissipates in order to complete the view we have on the energy fluxes.

2- It came out that three additional parameters should to be studied: two are related to the innovative system and the third is the bulb filling (Figure 9). Sulphur is not the only environmental acceptable substance whose vapour emits light at high temperature (molecular dissociation and recombination cycle); the two next elements of the same column of the Mendeleyev table, Selenium and Tellurium, have similar properties. The last of the column, Polonium, is dismissed for it is radioactive and very expansive. The advantage of elements of higher atomic mass is that they have much lower energy of dissociation (S2: 88 kcal./mol, Se2: 59 kcal./mol, Te2: 44 kcal./mol). Therefore the temperature of the plasma (high contain of dissociated molecules, no ionization) does not rises so much. This way, smaller bulb can be used without melting ad without forced cooling. This field of investigation is quite large because we expect that mixtures of the three elements may produce more interesting features.

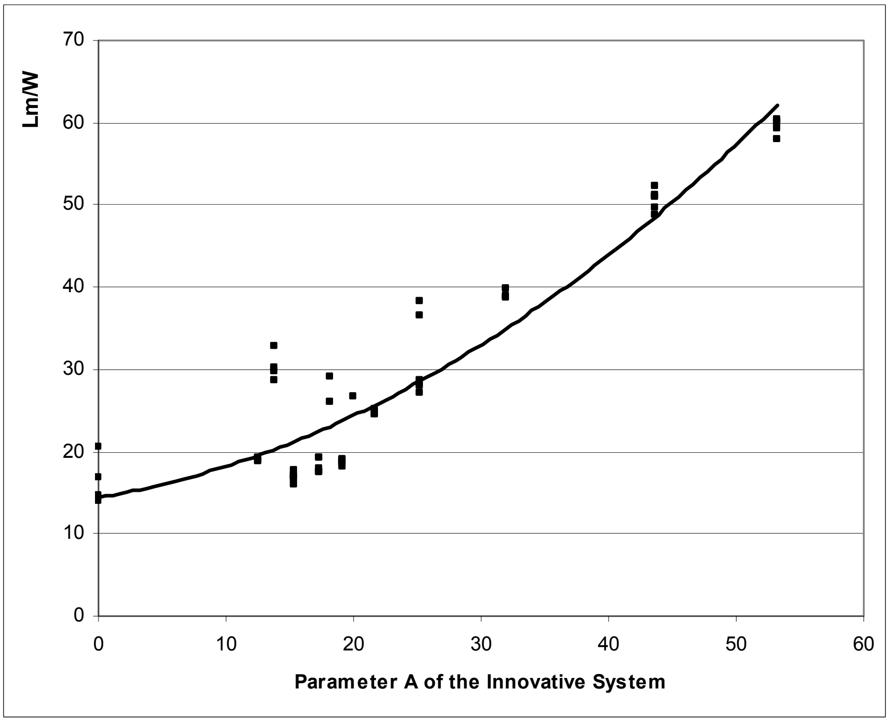

Figure 9: Tuning parameter A on Tellurium.

3- We have clarified that the bulb stays out of thermodynamic equilibrium when the lamp is working. According to Prigogine's principle about stability of non-equilibrium steady states [8], any regime in which the bulb filling sets in is stable because this system is a closed one. Yet if a state has been observed during long enough time, its domain of stability may not be very broad. Moreover, there are working points where different steady states can be obtained depending on the path taken to get to there. This is typical of bifurcations and could be induced by a positive feedback. For instance, the fact that microwave absorption increases with temperature could explain the bifurcations we have observed when varying the input power. A thorough experimental investigation of this aspect is necessary before stepping into the design of the electronic component that manages the warming-up and the regulation of the lamp.

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