PERGAMON

International Journal of Heat and Mass Transfer 43 (2000) 1223–1232

International Journal of
HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Modelling of an electric IR heater at transient and steady state conditions
Part II: modelling a paper dryer

Magnus Pettersson*, Stig Stenström

Department of Chemical Engineering 1, Lund University, P.O. Box 124, SE-221 00 Lund, Sweden

Received 18 February 1999; received in revised form 14 May 1999

Abstract

A model for an electric infrared (IR) paper dryer has been developed. The model includes non-grey radiative heat transfer between the different parts of the IR heater, as well as conduction in reflector material and convective cooling of surfaces. Such heat transfer calculations are combined with energy balances to provide a system of equations that simulates the behaviour of an electric IR dryer. Using IR module voltage as the only input, the model predicts the temperature of dryer components and cooling air, as well as the net radiation heat transfer to the paper sheet at steady state and transient conditions. The model has been used to investigate trends in efficiency and component temperature with changing voltage and paper grade. Emphasis has been on back reflector temperature and dryer efficiency. Also, the transients during start-up of an IR paper dryer have been investigated. The study indicates that the transients of the back reflector is important for the time needed to reach steady state heat flux at the paper sheet. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: IR; Paper; Drying; Modelling; Radiation heat transfer

1. Introduction

The most successful applications of electric infrared (IR) heaters include drying/curing of paint on metals and different drying operations in the pulp and paper industry. In our previous paper [1], a mathematical model for an electric IR heater was derived. For a given voltage the model was able to predict the temperature of the different heater components and also the transient behaviour when voltage changed. The model was compared with measurements on a lab scale heater in order to determine some heat transfer coefficients, as well as for model validation.

The model describes the IR heater working in a black environment, which is close to the experimental conditions. However, this is far from the ordinary situation in an industrial application. The influence of an industrial environment, however, can be studied if the black surrounding in the model is replaced with a more typical configuration. Such a study will also provide some information about the efficiency and transient behaviour of the IR heater in an industrial process. This work will extend the IR heater model with features typical for applications in the paper industry. The model will be used for a numerical investigation of electric IR dryer characteristics.

---

* Corresponding author. Tel.: +46-46-222-82-96; fax: +46-46-222-45-26.

E-mail address: Magnus.pettersson@kat.lth.se (M. Pettersson).

PII: S0017-9310(99)00202-1

Nomenclature

A	area (m^2)
C_p	specific heat (J/kg K)
E	blackbody emissive power (W/m^2)
$\varepsilon_{\lambda,i}$	emissivity of surface i at wavelength λ
F_{i-j}	view factor from surface i to surface j
G	irradiation (W/m^2)
h	heat transfer coefficient (W/m^2 K)
J	radiosity (W/m^2)
k	thermal conductivity (W/m K)
λ	wavelength (m)
m	mass (kg)
$Q_{\rm rad}$	radiation heat transfer rate (W)
$q_{\rm rad}$	radiation heat flux (W/m^2)
$r_{\lambda,i}$	reflectivity of surface i at λ
ρ	density (kg/m^3)
T	temperature (K)
t	time (s)
$\tau_{\lambda,i}$	transmissivity of surface i at λ

Subscripts

air	cooling air
back	back side
br	back reflector
ceram	ceramic
front	front side
g	protective glass
insul	insulation
λ	wavelength or wavelength interval
quartz	quartz
s	surrounding

Since paper is partially transparent in the near IR range of the spectrum, short-wave IR heaters are normally used with back reflectors to redirect transmitted radiation back to the paper sheet. The back reflector also absorb some radiation, heats up and start to radiate some energy. Ojala and Lampinen [2] have shown that the temperature of the back reflector is important for the overall system efficiency. They also show that higher basis weight of the paper sheet increases the efficiency at a specific back reflector temperature. However, it is well known that the back reflector temperature depends on the basis weight; a thicker paper transmits less radiation, which decreases the temperature of the back reflector. Their model does not provide any way of determining the back reflector temperature, and thus the influence of basis weight on efficiency. Extending our previous model to include a paper sheet and a back reflector will provide such information. As the optical properties of the paper sheet depend on moisture content and thickness, the influence of these properties will be studied.

2. Mathematical model

The parts of the model describing the interior of the heater will, of course, not change; only the exterior parts will change. All assumptions from our previous paper [1] remain unchanged, including the simplified, essentially one-dimensional geometry. The lamp, the reflector, and the protective glass are just as before, while a paper sheet and a back reflector have been added. The paper sheet is semitransparent, while the back reflector is assumed to be opaque. In Fig. 1, the principle of the extended model is illustrated and radiosities and irradiances are indicated for the different surfaces.

The back reflector is a structure using a reflecting ceramic on top to reflect radiation and an insulating mineral wool underneath to increase the surface temperature by reducing losses. The back reflector structure is cooled with cooling air to maintain the steel frame. Some of that cooling air is also blown out in the gap between the back reflector and the paper sheet in order to improve mass transfer and paper sheet stability. As the temperature increase of the paper sheet is limited and of no importance for the radiation heat transfer, a constant temperature of 60°C is assumed. Thus, the paper sheet will only be a 'radiation heat sink', and is not modelled in any other respect.

Since the equations for the heater will remain unchanged, not all parts of the model will be reviewed. Only the 'new' parts and some minor changes in the original model will be discussed. For a detailed discussion of the IR heater model, notes on assumptions, physical properties, view factors, etc., the reader is referred to our previous paper [1].

2.1. Energy balances

2.1.1. Protective glass

The protective glass is the only part of the original model that is changed. In the industrial enclosure there will be considerable cooling on both sides of the glass. The cooling of the exterior face of the protective glass, induced by the high speed of the paper sheet, is

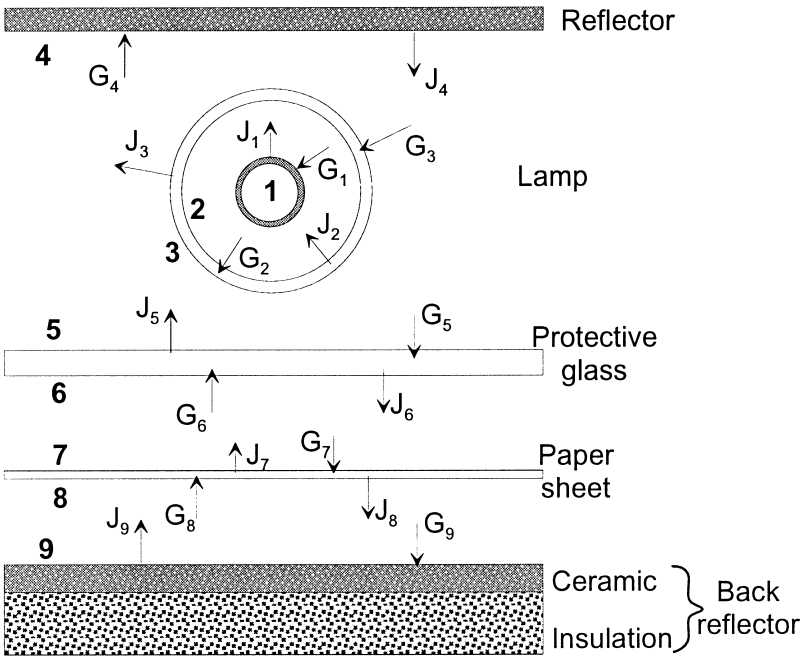

Fig. 1. Schematic of the extended model.

assumed to be equal to the cooling of the back reflector surface. The energy balance becomes

$$\frac{\mathrm{d}}{\mathrm{d}t}\left[C_{p,\mathrm{quartz}}\langle T_\mathrm{g}\rangle \cdot T_\mathrm{g}\right] = \frac{1}{m_\mathrm{g}}\left[Q_{\mathrm{rad,g}} - h_\mathrm{g}A_\mathrm{g}\left(T_\mathrm{g} - T_{\mathrm{air},2}\right) - h_{\mathrm{br,front}}A_\mathrm{g}\left(T_\mathrm{g} - T_{\mathrm{air,s}}\right)\right] \quad (1)$$

2.1.2. Back reflector

The back reflector will reach high temperatures, sometimes above 600°C. The temperature depends on the radiation absorbed and the convective cooling of both the front side and the back side. Since the ceramic material is insulated on the back side, the temperature gradients are expected to be large. A correct description of the temperatures and the heat loss will need to consider these gradients. The temperature in the back reflector is described according to Eq. (2), with combined radiation and convection boundary conditions on the front side (the side facing the paper and IR lamps) and convection on the back side. In order to keep the model simple, the temperature dependence of the physical properties is ignored.

$$\frac{\partial T_{\mathrm{br}}}{\partial t} = \frac{k}{\rho \cdot C_p}\frac{\partial^2 T_{\mathrm{br}}}{\partial y^2}$$

$$y = \mathrm{front} \quad k_{\mathrm{ceram}}\frac{\partial T_{\mathrm{br}}}{\partial y} = h_{\mathrm{br,front}}\left[T_{\mathrm{br,front}} - T_{\mathrm{air,s}}\right] - q_{\mathrm{rad,br}}$$

$$y = \mathrm{ceram/insul} \quad -k_{\mathrm{ceram}}\frac{\partial T_{\mathrm{ceram}}}{\partial y} = -k_{\mathrm{insul}}\frac{\partial T_{\mathrm{insul}}}{\partial y}$$

$$y = \mathrm{back} \quad k_{\mathrm{insul}}\frac{\partial T_{\mathrm{br}}}{\partial y} = -h_{\mathrm{br,back}}\left[T_{\mathrm{br,back}} - T_{\mathrm{air,s}}\right] \quad (2)$$

The convective cooling on the back side of the back reflector is due to a cooling air flow, whereas the cooling on the front side is a combination of some cooling air and the movement of the surrounding air induced by the high speed movement of the paper sheet. The movement will be similar on the outside of the protective glass.

2.1.3. Cooling air

The temperature of the cooling air in the IR heater has been calculated based on energy balances as described previously [1]. The air in the surroundings is a mixture of cooling air from the IR heater, cooling air from the back reflector, and ambient air in the paper machine. As the temperature of such air will differ from case to case and from day to day, a constant value of reasonable magnitude was chosen. The temperature of the surrounding air, $T_{\mathrm{air,s}}$, was set to 50°C.

2.2. Radiation heat transfer

2.2.1. Radiative exchange

The simplified geometry is shown in Fig. 1. Surfaces have been assigned an index, one for opaque surfaces and one for each side of semitransparent surfaces. Radiosity, J_i, and irradiation, G_i, for each surface have been indicated with corresponding indices. As in our previous work [1], one set of radiation balance equations is used for all 40 wavelength intervals, only the optical properties of each surface are changed with the wavelength. The radiosities for the additional surfaces in Fig. 1 can be expressed as in Eq. (3), whereas the equations for surface 1–6 are unchanged. The irradiation on each surface is determined as previously [1].

$$J_{\lambda,7} = r_{\lambda,7}G_{\lambda,7} + \tau_{\lambda,8}G_{\lambda,8} + \varepsilon_{\lambda,7}E_{\lambda,7}$$

$$J_{\lambda,8} = r_{\lambda,8}G_{\lambda,8} + \tau_{\lambda,7}G_{\lambda,7} + \varepsilon_{\lambda,8}E_{\lambda,8}$$

$$J_{\lambda,7} = r_{\lambda,9}G_{\lambda,9} + \varepsilon_{\lambda,9}E_{\lambda,9} \tag{3}$$

The corresponding area of the paper sheet and the reflector are taken equal to the area of the protective glass. No radiation is assumed to have escaped the system, i.e., the view factors $F_{6\text{–}7}$, $F_{7\text{–}6}$, $F_{8\text{–}9}$, and $F_{9\text{–}8}$ are taken to be unity. Anyone who have seen an IR paper dryer in operation knows that radiation does leave the dryer, and the last assumption is thus slightly inaccurate. In view of the assumptions that must be made regarding the heat transfer coefficients on the back reflector surfaces, the model results will be correct only in magnitude and trends. There is no point in taking radiation losses into account in order to improve the predictions.

The equations for irradiance and radiosity are solved and the net heat transferred by radiation to the different surfaces is determined as in our previous paper [1].

2.3. Properties and estimations

The physical properties of the heater components have been discussed in our previous paper [1], as have the heat transfer coefficients associated with the cooling air flow inside the IR heater. The optical properties of a 'used dirty back reflector' have been collected from the work by Ojala and Lampinen [2]. The optical properties of paper and paper coating have been taken from the work by Ojala [3]. As before [1], the spectral range 0.4–20 μm has been divided into 40 finite wavelength bands. Other properties of the back reflector are taken at 400°C, as given by the suppliers. For the ceramic part, the density 2500 kg/m^3, the specific heat 1150 J/kg K, and the thermal conductivity 2.0 W/m K are used. For the insulation, the density is 128 kg/m^3, the specific heat is 1130 J/kg K, and the thermal conductivity is 0.1 W/m K.

The present extended model introduces some more elements in the radiation balances and one more PDE to be solved. The numerical solution is obtained by the same principles and techniques as described for the heater model [1].

Two more heat transfer coefficients are also needed, one for the back side of the back reflector and one for the front side of the back reflector. The latter is also used for the external cooling of the protective glass. The heat transfer coefficient on the back side of the back reflector, $h_{\mathrm{br,back}}$, was estimated to be roughly 20 W/m^2 K. As it turned out, the solution was rather insensitive to the value of this number. An increase by 150% resulted in only few degrees change in back reflector surface temperature and in even less on other components.

The result was more sensitive to the heat transfer coefficient on the front side of the back reflector, $h_{\mathrm{br,front}}$. This heat transfer is dependent on a large number of different variables, such as machine speed and the direction and speed of cooling air blown out from the IR heater and the back reflector in order to improve paper sheet stability and improve drying. It is thus very hard to estimate this heat transfer coefficient. It is known, however, that the back reflector heats up to a bit over 600°C for a typical coated fine paper quality [4]. It was noted that at $h_{\mathrm{br,front}} = 45$ W/m^2 K, the steady-state back reflector surface temperature was just above 600°C when performing simulations with estimated paper properties for a 70 g/m^2 base sheet coated with 11.7 g/m^2. Therefore, that value will be used as a base case, and the influence of a 33% increase and decrease in this value will be illustrated in the results below. Such changes are not only attributed to the uncertainty in the numerical value of the coefficient, but can also be interpreted as the result of increasing or decreasing the machine speed.

3. Results

3.1. Steady state

When introducing non-black surfaces in front of the IR heater, radiation is reflected back to the heater. This results in increased absorption by the heater components and increased temperatures, when compared to a heater working in a black environment. The increase will depend on the properties and the temperature of the reflecting object. In the case of a paper sheet and a back reflector, the situation is even more complex, since the properties of paper depend on the specific grade, coating, moisture ratio, etc. Furthermore, different properties of the paper will result in different back reflector temperatures, which also affects the heater. It is also obvious that all these effects will depend on the voltage, i.e., on the electric power. As the focus of the discussion below will be on the back reflector and the fraction of power transferred to the paper sheet, i.e., the process efficiency, only a rough indication of the steady state temperatures in the IR heater will be given. Note that voltages given refer to the voltage supplied to the IR module, not to the individual lamps.

The temperature of the filament will increase by approximately 25°C at 130 V and 115°C at 400 V. Thus, the filament temperature is increased to more than 2330 K at 400 V. The temperature increase means that the resistivity, and thus the resistance of the lamp, will increase for the same voltage compared with the IR heater with a black surrounding, which results in a lower electric power. However, the decrease is less than 6%. The temperature of the lamp glass will increase about 25°C at 130 V. At 400 V, the increase is about 250°C. Thus, the temperature of the lamp glass is unrealistically high for some of the results presented below, which might indicate that the convective heat transfer coefficient for the cooling of the lamp has been chosen too low in the previous paper [1]. As pointed out in the conclusions of that work, the cooling of the lamp glass can be increased noticeably without causing large errors when comparing it with the available measurements. The temperature of the reflector and the protective glass is increased by about 5°C at 130 V, but at 400 V the temperature increase is about 150°C. The increase in the temperature of all these components also results in a higher temperature of the cooling air at the outlet. The increase is only 1–2°C at lower voltages, but as much as 25–30°C at the higher voltages. At 400 V, the energy carried off with the cooling air has thus increased more than 35%, i.e., from roughly 32% of the electric power to 48%. This means that the net fraction of energy leaving the IR heater as radiation has been drastically reduced. This result is in good agreement with experimental findings [6].

Fig. 2 shows the fraction of electric power transported to the paper sheet by radiation and the back reflector temperature at steady state at different voltages. The simulations have been done for a coated fine paper grade, 70 g/m^2 base paper and 11.7 g/m^2 coating. The properties for such a sheet have been estimated from the data presented by Ojala [3], according to the model presented by Pettersson and Stenström [5]. Note that a coated paper has different reflectivity on the different sides. At high voltage, the back reflector temperature is just above 600°C and the efficiency is 38%, with both these findings in accordance with experience [6]. Both the efficiency and the back reflector temperature drop as the voltage is reduced. The dashed lines indicate the influence of a 33% increase or decrease in $h_{\mathrm{br,front}}$. An increase in $h_{\mathrm{br,front}}$ results in lower back reflector temperature and lower efficiency, i.e., a lower fraction absorbed in the paper sheet.

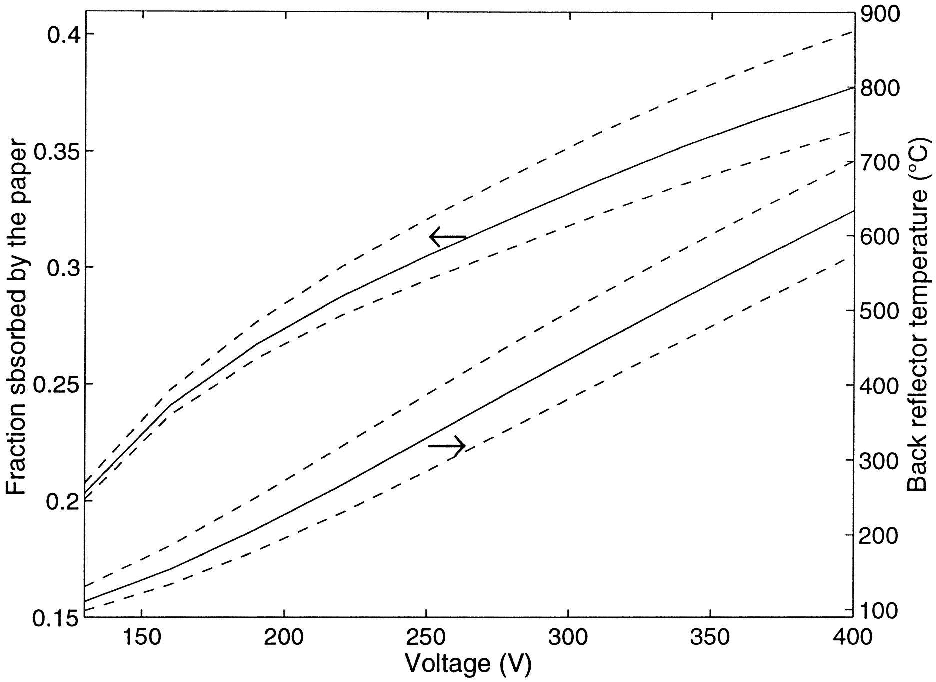

Fig. 2. Fraction of electric power absorbed by a coated fine paper sheet and the back reflector temperature at different voltages. Influence of a 33% increase or decrease in $h_{\mathrm{br,front}}$ is indicated with dashed lines.

Based on some assumptions, Ojala and Lampinen [2] showed that the efficiency of an electric dryer should increase when reducing the power level. In view of the results presented in Fig. 2, these assumptions should be questioned. It is also possible that the results presented in Fig. 2 can explain some of the spread in experimental data on infrared dryer efficiency. These results are normally given without reference to IR dryer power level, which is clearly a very important parameter.

Ojala [3] presents the optical properties of bleached paper at five different basis weights. These properties have been used in the model at 400 V to see how the efficiency and the back reflector temperature are affected. Generally, a higher basis weight means a higher reflectivity and lower transmissivity. There is also an increase in the absorptivity. The influence of basis weight is shown in Fig. 3. Increasing basis weight means less transmitted radiation, and thus the back reflector temperature decreases. At the same time, the efficiency increases due to the higher absorptivity. The heater components also increase some 5–15°C due to the increased reflections from the thicker paper sheets and are also partly responsible for the increased efficiency. The increase in efficiency is weaker, however, than indicated by Ojala and Lampinen [2], who assumed constant temperature of both back reflector and IR heater components.

The influence of $h_{\mathrm{br,front}}$ is indicated with dashed lines. A low value of $h_{\mathrm{br,front}}$ results in a higher back reflector temperature and a higher efficiency. It is interesting to note that the influence of basis weight on efficiency is more pronounced when the higher value of the convective heat transfer coefficient is used.

The results in Fig. 3 are interesting in that they support the experience [4] that at really low basis weights the back reflector design needs to be reconsidered in order to reduce temperature-induced stresses in the back reflector material. The results indicate that at basis weights below 60 g/m^2 the temperature of the back reflector becomes higher than 700–800°C, which could result in severe temperature stresses.

Ojala and Lampinen [7] present data on the optical properties of a 41.1 g/m^2 dry weight bleached paper sheet at different moisture ratios. Generally, the reflectivity decreases with increasing moisture ratio and the absorptivity increases. The transmissivity depends in a more complicated way on the moisture ratio. At some wavelengths the transmissivity increases, and at others decreases, with increasing moisture ratio. In some wavelength ranges, the transmissivity first decreases and then increases again. The properties of the paper

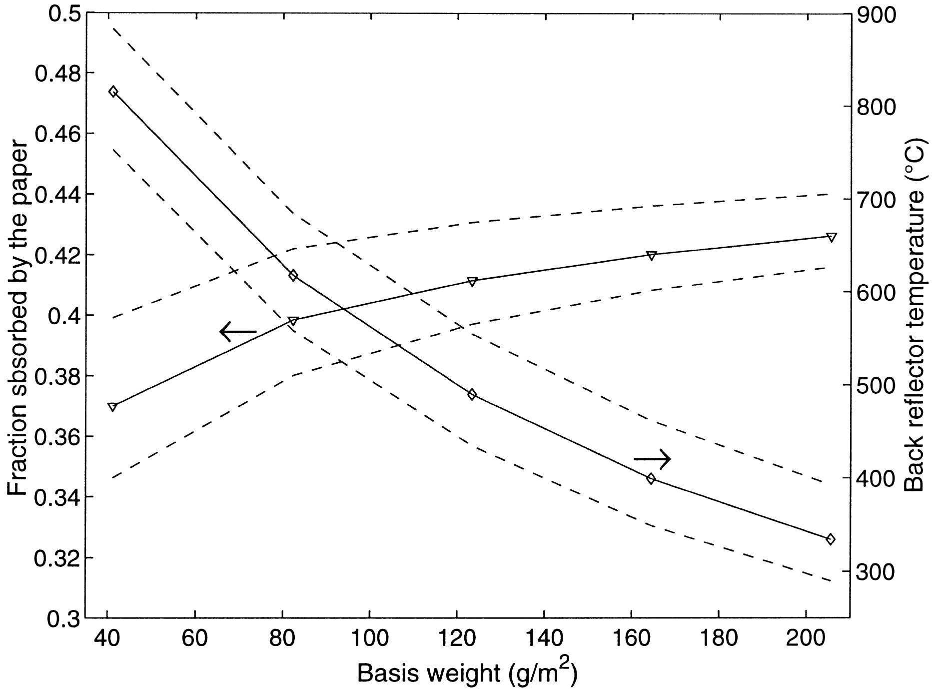

Fig. 3. Fraction of electric power absorbed and the back reflector temperature at different dry basis weights at 400 V. Influence of a 33% increase or decrease in $h_{\mathrm{br,front}}$ is indicated with dashed lines.

sheet at the four different moisture ratios investigated were used in the model at 400 V to see how the efficiency and the back reflector temperature are affected by changes in moisture ratio. The steady state results are shown in Fig. 4.

Fig. 4 shows that the efficiency increases with increasing moisture ratio, though the increase is limited to some percentage of the total electric power. The relative increase is still important. The back reflector temperature decreases as the moisture ratio increases, but at high moisture ratio the temperature increases again. This means that at low-moisture ratio, the increased absorption by the paper sheet reduces the energy transferred to the back reflector. The effective transmissivity is obviously increasing again at the highest moisture ratios, resulting in the increase in back reflector temperature. Because this temperature increase results in higher efficiency, it can be expected that the increase in efficiency at the highest moisture ratios is not only due to the increase in absorptivity.

The reduction in paper reflectivity with increasing moisture ratio also results in a decrease in temperature of the IR heater components. From moisture ratio 0.06 to 1.02, the filament temperature decreases with over 30°C at the same voltage. The temperature of lamp glass, reflector, and protective glass decreases with 50–80°C. This results in a lower cooling air outlet temperature and thus lower energy losses with the cooling air. The influence of $h_{\mathrm{br,front}}$ is roughly constant on both back reflector temperature and efficiency. Increasing the heat transfer coefficient results in lower back reflector temperature and lower efficiency, and vice versa.

3.2. Transient conditions

The step response of the combined system with the IR heater, paper, and back reflector is indicated in Fig. 5, when increasing the voltage from 0 to 400 V. The heat transfer coefficient $h_{\mathrm{br,front}}$ has been set to 45 W/m^2 K. Data for the coated fine paper described above was used. Fig. 5 shows the temperature of the filament and lamp glass, the temperature on both sides of the reflector in the IR heater, and the temperature on both sides of the back reflector. As before, the filament temperature increases rapidly to a very high temperature, though a small final increase occurs over 1–2 min. The temperature of the lamp glass and the reflector increases noticeably during 4–5 min before reaching steady state values. As indicated, the difference in temperature between the front side and the back side of the reflector is only some 20°C. The temperature of the back reflector takes an even longer time to develop a steady state, about 10 min. This is due mainly to the mass of the ceramic layer. The low density of the insulation results in a quite small additional time lag due

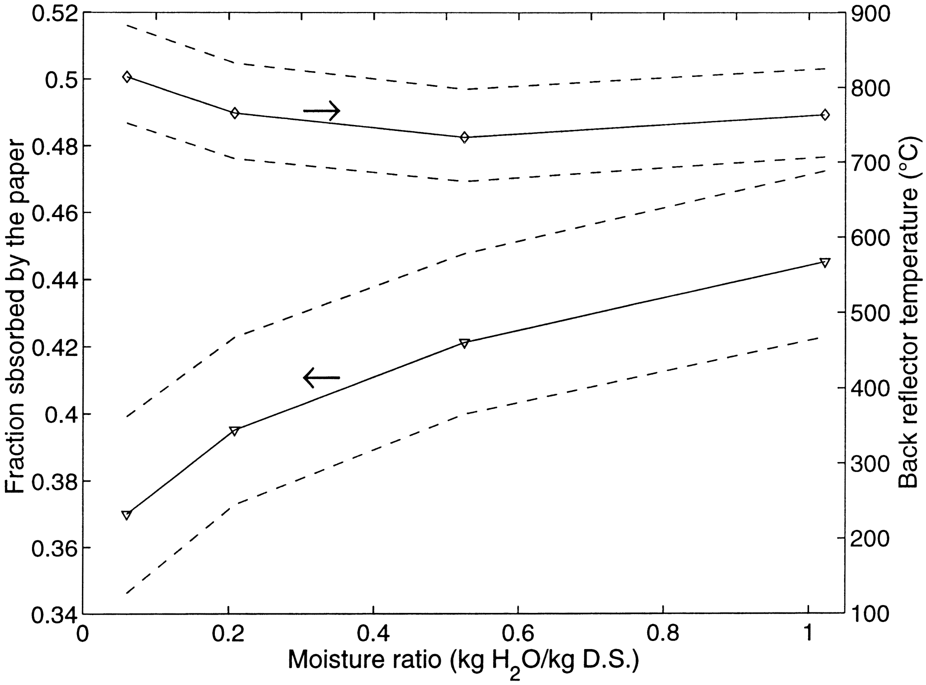

Fig. 4. Fraction of electric power absorbed and the back reflector temperature at different moisture ratios at 400 V for a 41.1 g/m^2 dry weight sheet. Dashed lines indicates the influence of a 33% increase or decrease in $h_{\mathrm{br,front}}$.

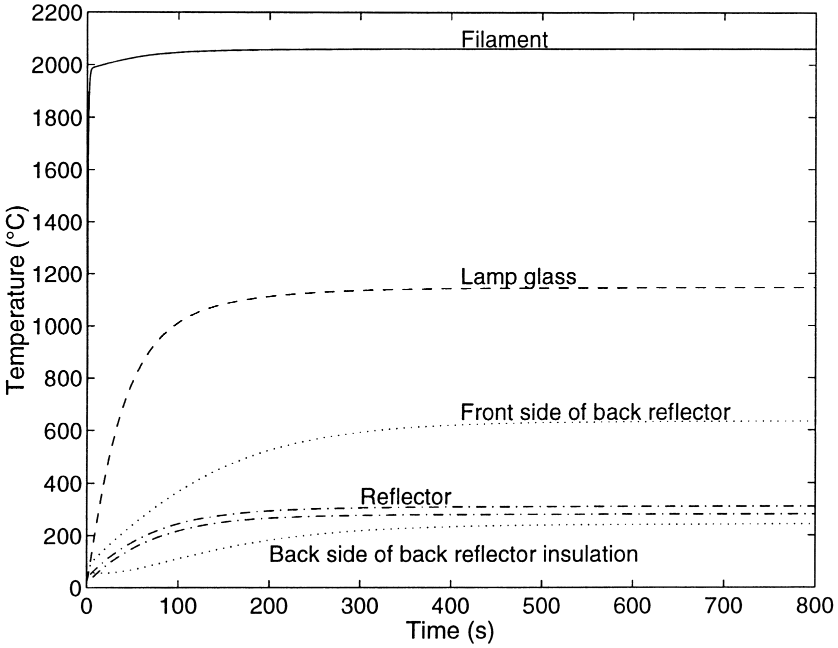

Fig. 5. Step response of IR heater and back reflector temperatures when increasing the voltage from 0 to 400 V. Properties of paper sheet as for a coated fine paper.

to the insulation. The temperature gradient within the ceramic part is small, some 15–20°C, whereas the temperature gradient in the insulation is very large, almost 400°C.

The corresponding normalised step response in heat transported to the paper sheet is illustrated in Fig. 6. As with the IR heater alone, the energy transferred increases rapidly over the first 5–10 s, but then a period of almost 10 min is required to reach steady state, the full operating capability of the dryer system. For the IR heater alone, about 82% of full power is reached within seconds. For the transfer of heat from IR heater to paper with a back reflector, only 57% is reached within seconds. The increased thermal mass of the system due to the introduction of the back reflector delays the response. At the same time, this is an excellent illustration of the importance of the back reflector. The efficiency of the system is improved as the back reflector comes into operation. It is clear, however, that the term 'instant on' often used by suppliers needs some moderation.

4. Conclusions

The model for an electric IR heater [1] has been extended with features typical for an IR paper dryer, and the influence of power level and paper grade has been investigated. The results for the lamp glass temperature indicate that the value for the cooling air heat transfer coefficient for this component estimated previously [1] is too low.

When extending the model to include a paper sheet and a back reflector, the same kind of physical description as in the basic model has been used. It is reasonable to expect this to be an equally good description, even though no experimental results are available for determination of heat transfer coefficients. The results can thus represent only trends and magnitude. However, it is an interesting feature not to have to set the temperature of the different components of the IR dryer a priori, as has been done in all previous work. For example, Ojala and Lampinen [2] performed a number of simulations with different radiative properties of the back reflector. They were still not able to determine the effect of these changes since they did not know how the change affects the back reflector temperature. In the present model, the temperature is part of the solution. Studies indicate that the efficiency is rather insensitive to the reflectivity of the back reflector. A lower reflectivity results in a higher temperature and the absorbed radiation is re-emitted. The increased convective losses are cancelled by the improved absorption by the longer wavelengths emitted from the back reflector. As no energy balances have been used for the paper sheet, the model is more or less a study of the effect of changing the properties of an isothermal semitransparent window between the IR heater and the back reflector. This does not significantly reduce the usefulness of the model.

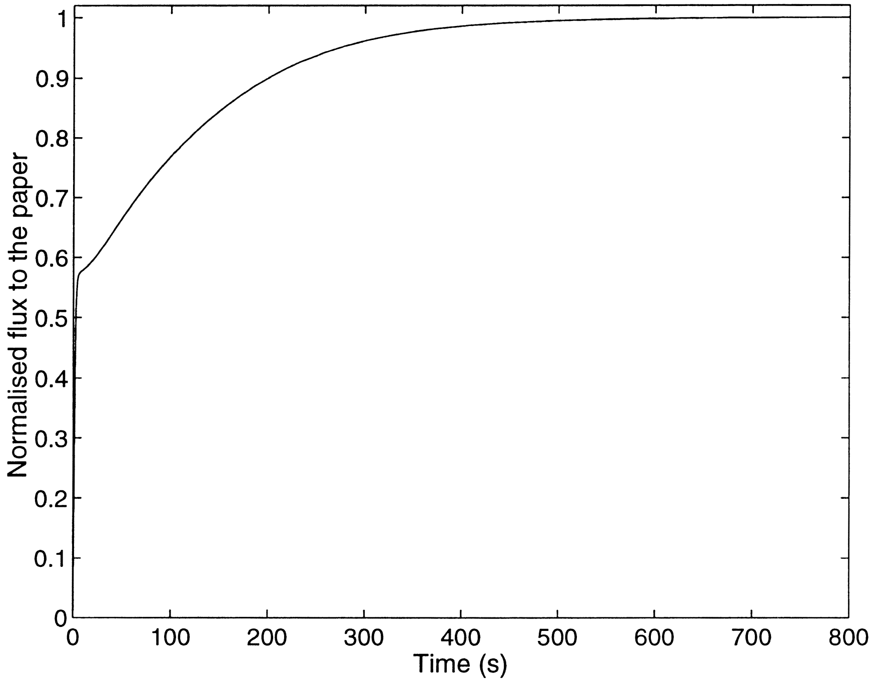

Fig. 6. Normalised step response in heat transported to the paper sheet when increasing the voltage from 0 to 307 V. Properties of paper sheet as for a coated fine paper.

In agreement with the assumption of symmetry in all directions, no radiation was allowed to escape the system. This means that the temperatures of most components are probably somewhat overestimated. The combined assumption of a clean protective glass in combination with the assumption of no radiation losses, would result in an overestimation of the efficiency as well. The efficiency at high voltage is normally in the range of 35–45%, even with very varying values for the heat transfer coefficients. This is also in rough agreement, though somewhat higher, with experimental work [6,8,9]. It must be remembered, of course, that all this modelling work relies to a large extent on optical properties in the IR of various materials. Especially in paper, the optical properties are likely to vary a great deal between qualities based on different pulps and production parameters.

Acknowledgements

Mr. Klas-Göran Dahl, Itronic Sweden AB, is acknowledged for sharing some of his experience and knowledge of IR heaters and their application in the paper industry. Sydkraft and SGC are acknowledged for financial support.

References

[1] M. Pettersson, S. Stenström, Modelling of an electric IR heater at transient and steady state conditions. Part I: model and validation, International Journal of Heat and Mass Transfer 43 (2000) 1209–1222.

[2] K.T. Ojala, M.J. Lampinen, Modeling, measurements and efficiencies of infrared dryers for paper drying, in: A.S. Mujumdar (Ed.), Handbook of Industrial Drying, 2nd ed., Marcel Dekker, New York, 1995, pp. 931–976.

[3] K.T. Ojala, Studies on infrared drying of paper, use of integrating spheres in FTIR-measurements, and heat and mass transfer inside paper, Ph.D. thesis, Helsinki University of Technology, 1993.

[4] Klas-Göran Dahl, Itronic Sweden AB, Personal communication.

[5] M. Pettersson, S. Stenström, Absorption of infrared radiation and the radiation transfer mechanism in paper. Part I: Theoretical model, Journal of Pulp and Paper Science 24 (11) (1998) 349–355.

[6] M. Pettersson, S. Stenström, Experimental evaluation of electric infrared dryers, TAPPI Journals (accepted).

[7] K.T. Ojala, M.J. Lampinen, Optical properties of wet paper and simulation of the effect of autoprofiling on gas-fired IR drying, in: Drying '92, 1992, pp. 1039–1050.

[8] F. Evin, H. Junginger, P. Le Peurian, Le sunair, Un nouveau mode de séchage du papier utilisant les rayonnements IR électriques, in: UIE XIII Congress on Electricity Applications, 1996, pp. FIN 69–FIN 76.

[9] A. Lematre, D. Glise, Radiation heating to increase machine production: comparison of various technologies, in: The Helsinki Symposium on Alternate Methods of Pulp and Paper Drying, Helsinki, 1991, pp. 405–424.