

MATHEMATICAL MODELLING OF STRAW BALE COMBUSTION IN CIGAR-BURNERS

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ABSTRACT

This paper describes a computer model for the calculation of the steady and non-steady behaviour of straw bales subject to surface combustion in cigar burners. The mathematical formulation is one-dimensional and the flow of gas through the straw bales is described by means of Darcy's law for flow through a porous medium. The computer model is able to predict flow rate, temperature and composition of gas and straw as function of axial length and time. Calculated results are compared to measurements of temperature- and gas composition profiles within the burning straw bales. It is observed that the straw bale temperatures as well as the outlet gas composition are predicted reasonably well. Calculations have been carried out in order to assess the implication of a straw bale feed stop in a 3 MW district heating plant fueled with Heston straw bales. The results indicate serious disturbances in the performance of the burner.

INTRODUCTION

A computer model, STRAW, has been developed for the calculation of the steady and non-steady behaviour of surface combusting straw bales¹. Paralleling the theoretical efforts experiments have been carried out with the purpose of measuring temperature and concentration profiles within the burning straw bales as well as in the furnace room²⁻³. The measurement have been used in the validation of STRAW.

The principle of surface combustion of straw bales is illustrated in figure 1 after Gundtoft⁴. The straw bales are fed from the left at a rate corresponding to the combustion rate in such a way that the burning bale front remains at a fixed position. The figure shows the different process areas. Due to diffusion and subsequent condensation of water vapour a zone of straw with a water content higher than that of raw straw may appear. As the temperature rises the straw is dried and after that it undergoes pyrolysis. The required heat is transported from the burning surface through thermal conduction and radiation. When the devolatilization of the straw is finished straw char remains. The burning of the char finally results in a layer of ash or slag. Primary air is injected for the combustion at the straw surface, while oxygen for the combustion in the furnace room of the remaining gases is provided by a secondary air stream.

THE COMPUTER MODEL STRAW

For a more detailed description of the mathematical model conf. reference 1.

Assumptions. The following assumptions are made:

1. The system is one-dimensional in space.
2. The cross sectional area of the straw bales is constant.
3. The gas is described as an ideal gas.
4. The flow of gas through the straw grid is described by means of Darcy's law for flow through a porous medium.

5. The velocity of the straw grid is constant in the axial direction (but not in time).
6. The porosity and the permeability of the straw grid depends upon time and the location in the bale.
7. Only water vapour diffusion is considered at the moment.
8. Straw-gas and gas-gas thermal radiation is neglected in the straw bales.

Basic Equations.

Mass conservation for component no. i in the gas phase:

$$\frac{\partial m_g^i}{\partial t} + \frac{\partial (m_g^i u_g)}{\partial x} = \Gamma^i + S_g^i \quad (1)$$

Mass conservation for component no. i in the straw:

$$\frac{\partial m_h^i}{\partial t} + u_h \times \frac{\partial m_h^i}{\partial x} = -\Gamma^i - S_h^i \quad (2)$$

Energy equation for the gas phase:

$$\frac{\partial e_g}{\partial t} + \frac{\partial (e_g u_g)}{\partial x} = Q_g + \sum_i (\Gamma^i h_p^i + S_{in_j}^i h_{in_j}^i) \quad (3)$$

Energy equation for the straw:

$$\frac{\partial e_h}{\partial t} + u_h \times \frac{\partial e_h}{\partial x} = Q_h - \sum_i \Gamma^i h_p^i + \frac{\partial}{\partial x} \left(\lambda_h^* \frac{\partial T_h}{\partial x} \right) \quad (4)$$

Momentum for the gas phase (Darcy's law):

$$u_g = u_h - \frac{K}{\mu_g} \left(\frac{dp}{dx} + g \cos \Theta \rho_g \right) \quad (5)$$

Symbols:

g	Acceleration of gravity [m/s ²]
K	Permeability of straw grid [m ²]
p	Gas pressure [Pa]
Q	Heat production per unit volume [W/m ³]
S	Mass source/sink [kg/m ³ /s]
T	Temperature [C]
u	Velocity [m/s]
Γ	Transfer of mass from straw grid to the gas phase per unit volume and time [kg/s/m ³]
h	Enthalpy [J/kg]
λ^*	Effective thermal "conductivity" of straw grid which takes into account heat conduction as well as thermal radiation [W/m/C]
μ	Dynamic viscosity of gas [kg/m/s]
ρ	Density of gas [kg/m ³]
Θ	Angle between x-axes and vertical [degrees]

EXPERIMENTAL DESIGN

A test facility for burning straw bales has been constructed (see fig. 2). It is capable of burning straw packed in small bales of 10-12 kg each by means of surface combustion, i.e. the bale is not torn up, but is burnt from one end to the other. Primary air is being injected directly to the straw surface by means of air nozzles. The remaining part of the air is being added in the main duct, giving an excess air ratio of about 1.7. Directly in front of the straw surface is an electrically heated zone giving a heat flux to the straw, and thereby illuding a combustion chamber with hot walls. By means of probes inside the straw bale, measurements of temperatures and gas concentrations during the whole combustion process have been performed. For a more detailed description see references 2 and 3.

COMPARISON TO MEASUREMENTS

Straw bales constitute a very inhomogeneous fuel. Fig. 3 shows measured temperatures for four "near identical" experiments. The calculated temperatures are shown as well. The burning straw bale surface is located where the temperature reaches its first maximum around 1000 centigrade (around $x = 230$ mm in the figure). It is seen that the rise in straw bale temperature close to the burning surface as well as the temperature at the surface are predicted reasonably well.

The measured concentrations at the burning surface shown in table 1 are averages for the four experiments. It is seen that the gas concentrations of CO_2 , CO and C_xH_y are also predicted reasonably well although the amount of C_xH_y is slightly underestimated. The gas composition inside the straw bale close to the burning surface (which is not shown here) is not predicted well enough. This is believed to be due to the fact that the model does not account for turbulent diffusion of the gas phase components. In the calculation it has been assumed that 80 % of the primary air is available for combustion at the straw bale surface.

CALCULATED FEED STOP IN CIGAR BURNER

One event which is known to cause problems in a cigar burner in terms of a deterioration of the combustion and increased pollution is the stop in the straw bale feeding which occurs in some plants in connection with the delivery of a new straw bale. Calculations have been carried out in order to assess the implication of a straw bale feed stop in a 3 MW district heating plant fueled with Heston straw bales.

The straw bale feed and air injection are interrupted for 60 seconds and then continued from $t = 75$ sec. at the previous rates. In fig. 4 are shown the inlet and exit mass flow rate of straw carbon W_{in}^C and W_{hex}^C respectively. The amount fed at the inlet drops to nil after 15 sec. and increases to the initial rate at 75 sec. The exit value is zero initially at the normal operating conditions. This means that all the straw carbon is burned at the straw surface. It is seen however, that when the feeding starts again at $t = 75$ sec then W_{hex}^C becomes positive for a short period of time (≈ 5 sec). In other words, unburned straw carbon falls into the combustion chamber when the straw feeding is restarted. The reason is that the temperature at the straw surface drops about 200 degrees during the feed stop, conf. fig. 5.

SUMMARY AND CONCLUSIONS

A computer model, STRAW, has been developed for the calculation of the steady and non-steady behaviour of surface combusting straw bales. Model predictions have been compared to measurements of temperature- and gas composition profiles within the burning straw bales and calculations have been carried out in order to assess the implication of a straw bale feed stop in a 3 MW district heating plant fueled with Heston straw bales.

Comparisons between calculated and measured results show that:

- The rise in straw bale temperature close to the burning surface as well as the temperature at the surface are predicted reasonably well.
- The concentrations of CO_2 , CO and C_xH_y in the exit gas are also predicted reasonably well although the amount of C_xH_y is slightly underestimated.
- The gas composition inside the straw bales close to the burning surface is not predicted well enough probably because the model does not account for turbulent diffusion of the gas phase components.

It has been shown that an interruption of the feed for 60 sec causes violent disturbances in the computed performance of the burner. Unburned straw carbon is pushed into the combustion chamber when the straw feeding is restarted. In order to maintain good burner performance it is essential to avoid this behavior. This can be done by introducing a continuous feeding system which maintains the straw bale feeding rate at the operating value.

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REFERENCES

1. Bech, N. "Modelling of the Vølund Cigar Burner by means of the Computer Model STRAW", Risø-R-817, Risø National Laboratory, Roskilde, Denmark, 1995.
2. Wolff, L. "Forsøgstopstilling til forbrænding af halmballer ('Pyrolyseforsøg')", Risø-R-721 (DA) Forskningscenter Risø, december 1993.
3. Wolff, L. and Bech, N. "Surface combustion of straw bales, a test facility for pyrolysis investigations", 8th European Conference on Biomass for Energy, Environment, Agriculture and Industry, Vienna, 3-5 October, 1994.
4. Gundtoft, S. "Forbrænding af halm i mindre anlæg", Jysk Teknologisk, august 1989.

	O ₂	CO ₂	CO	C _x H _y
Measured	0.04	0.14	0.14	0.015
Calculated	0.04	0.15	0.14	0.011

Table 1: Comparison of measured and calculated concentrations in the gas at the burning straw bale surface

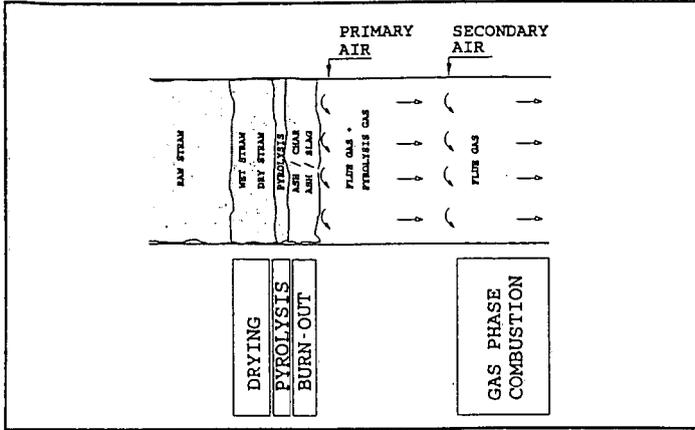


Figure 1: Surface combustion of straw. Definition of processes and zones.

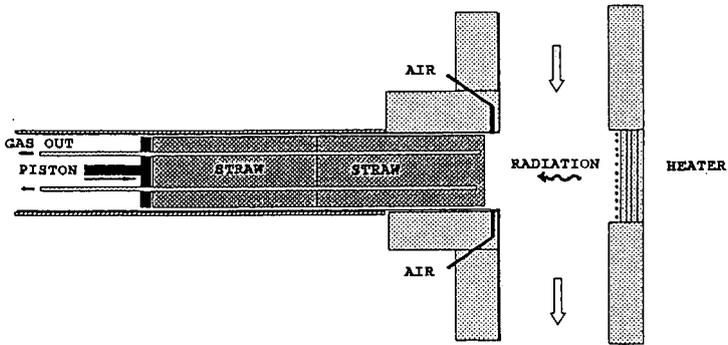


Figure 2: Experimental setup.

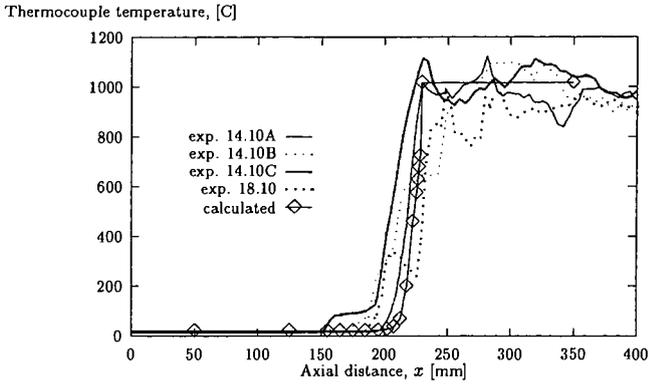


Figure 3: Comparison of measured and calculated thermocouple temperatures

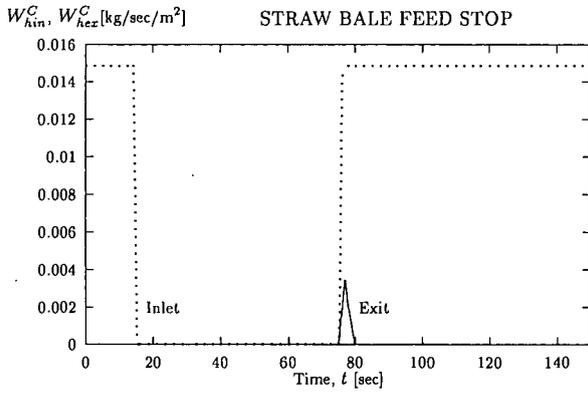


Figure 4: Inlet and exit mass flow rate of straw carbon for straw bale feed stop

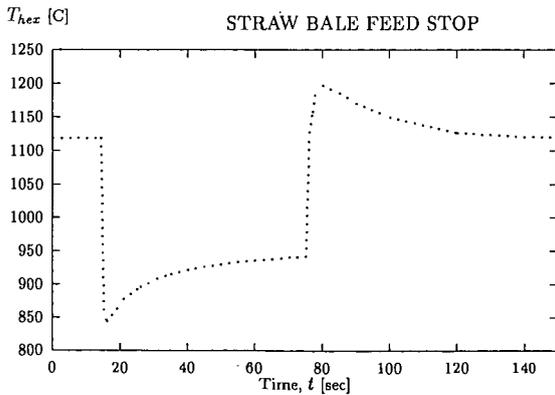


Figure 5: Calculated exit straw temperatures for straw bale feed stop