# How 10 Years of Physical Assumptions Led to the Development of the Balbi Model, From Laboratory Scale to Field Scale

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**Abstract**—This work deals with the construction of a fire behavior model that can be easily used by people involved in firefighting or in environmental planning. The model has to provide the main physical characteristics of the fire front (rate of spread, flame tilt angle, flame height, flame length, flame temperature etc.). As this model has to be a universal one, it can be applied to any surface fire configuration without any change in the model.

**Keywords:** physical model, radiation, convection, rate of spread

## INTRODUCTION

Ten years ago, the main part of fire propagation models was split up in empirical models (e.g. the well-known Rothermel model, Rothermel 1972) and complete physical models (the so called multiphase models incorporated into simulators such as Firestar, Firetec or WFDS Linn et al. 2007; Mell et al. 2005; Morvan et al. 2009; Morvan 2014). Simplified physical models were yet another type of model (for instance Koo et al. 2005; Pagni and Peterson 1973) which were physics-oriented enough with a computational time close to zero.

Our goal, at the University of Corsica, was to build a simplified surface fire propagation model (no crown fire model) that could be used by people involved in firefighting or in fire-management. This model had to be physics-oriented, three-dimensional, faster than real time and provide a good accuracy. The use of simplified physical laws had to give the main physical characteristics of a fire front (rate of spread, flame tilt angle, flame temperature, etc.) as a function of the wind speed, the terrain slope angle, the fuel moisture content and other fuel characteristics. This model was built in five steps from a simple model to a complete model working at the field scale.

In order to obtain a simplified physical model, the first important thing is to avoid using partial differential equations, which need strong assumptions on the gas phase. Then we have to consider average values of the variables (e.g., the mean flame temperature). Next, we have to consider simplified physical laws (e.g., simplified mass or energy or preheating balance). Finally, the ROS appears to be the solution of an algebraic equation.

## A RADIATIVE ONLY SIMPLIFIED PHYSICAL MODEL

### 2007—The First Operational Model

This first operational model took into account three energy transfer modes:

1. Flame base radiation (radiation from the fuel burning particles area). The burning fuel/unburnt fuel interface is assumed to be a black radiant panel and we use a usual Stefan-Boltzman modeling.
2. Flame radiation with the flame as a grey radiant panel.

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3. Convective cooling in front of the flame. This cooling leads to a strong assumption: the flame radiation only impinges the unburnt fuel under the flame.

This model (Balbi et al. 2007) was tested in litter experiments with success but some weaknesses remain. Indeed, some equations of the model come from empirical laws (for instance, the flame height is computed with the McCaffrey correlation). Another weakness lies in the definition of flame radiation. And last but not least, the simplified model has 3 model parameters.

### 2010—Model Improvements

Three years later, three improvements were made. First, we changed the McCaffrey correlation for a physical law obtained with a simplified vertical momentum balance. We also came up with a better modeling for the radiative fraction and we introduce a fresh cooling which models the backfire better. The two main equations of the model are the following (Balbi et al. 2009; Balbi et al. 2010):

$$R = R_b + A\,R\,\frac{1+\sin\gamma-\cos\gamma}{1+\frac{R\cos\gamma}{r_0}} \quad (1)$$

$$\tan\gamma = \tan\alpha + \frac{U}{u_0} \quad (2)$$

where $R$ is the rate of spread, $R_b$ is the flame base radiation, $A$ is a radiant coefficient, $r_0$ is a model parameter, α is the terrain slope angle, $U$ is the normal component of the wind speed and $u_0$ is the upward gas velocity.

This improved model was applied to a set of laboratory experiments with strong winds (up to 11 m $s^{-1}$) and non-parallel wind & slope. However, this model still neglects convection and then poorly represents laboratory experiments with well-ordered, vertically-oriented fuel bed.

### 2011-2014—Model Developments

The improved model has been used in several manners over 4 years. The first one concerns its incorporation into the ForeFire simulator (http://forefire.univ-corse.fr). It also acted as input data for our analytical model for acceptable safety distance (Rossi et al. 2010; Rossi et al. 2011). Thanks to the model, we were able to find two non-propagation criteria, a condition on the extinction moisture and another on the packing ratio (Balbi et al. 2014a). Finally, the last development concerns eruptive fires. We believe, as Viegas did, that the convective flow induced by the fire is responsible for eruption's triggering. We produced a physical modeling of what we called induced wind, and our model is able to compute the threshold terrain slope angle from which eruption is sure (Balbi et al. 2014b).

## A RADIATIVE-CONVECTIVE SIMPLIFIED PHYSICAL MODEL

### 2016—A Convective Model

The point is to determine the flow of the hot gases so as to check the validity of a convective model, this model has to be confronted to experiments with well-ordered and vertically-oriented fuel beds. Indeed, many authors, from Wolff, carrier and Fendell (Wolff et al. 1991) to Finney (Finney et al. 2013) proved that convection is the dominant heat transfer mode in this type of experiments. So, with those specific fuel beds, radiation from the flame base is still considered but is expected to be not very important because of the well-ordered fuel particles.

As flame radiation impinges a very small surface of the fuel bed because of the verticality of fuel particles, it will be neglected. As several authors did, we consider that the flame is quasi laminar in its first half above the vegetal stratum and then it acts as a barrier to the air flow. So, we take into account the flow inside the flame base. A gas particle inside the flame base is subjected to wind speed and upward gas velocity. Some gas particles go out of the flame base through its top and then go into the flame but some gas particles go out of the flame base through the burning/unburnt fuel interface. This hot gas flow creates a contact flame which ignite the unburnt fuel. This contact flame is the modeling of the fingers of fire observed by Rothermel and Anderson (Rothermel and Anderson 1966).

The convective model has been applied to 172 laboratory fires as found in the literature (Chatelon et al. 2017).

We can observe (fig. 1, left) the good agreement between predicted and observed ROS with a very small Normalized Mean Square Error, a Fractional

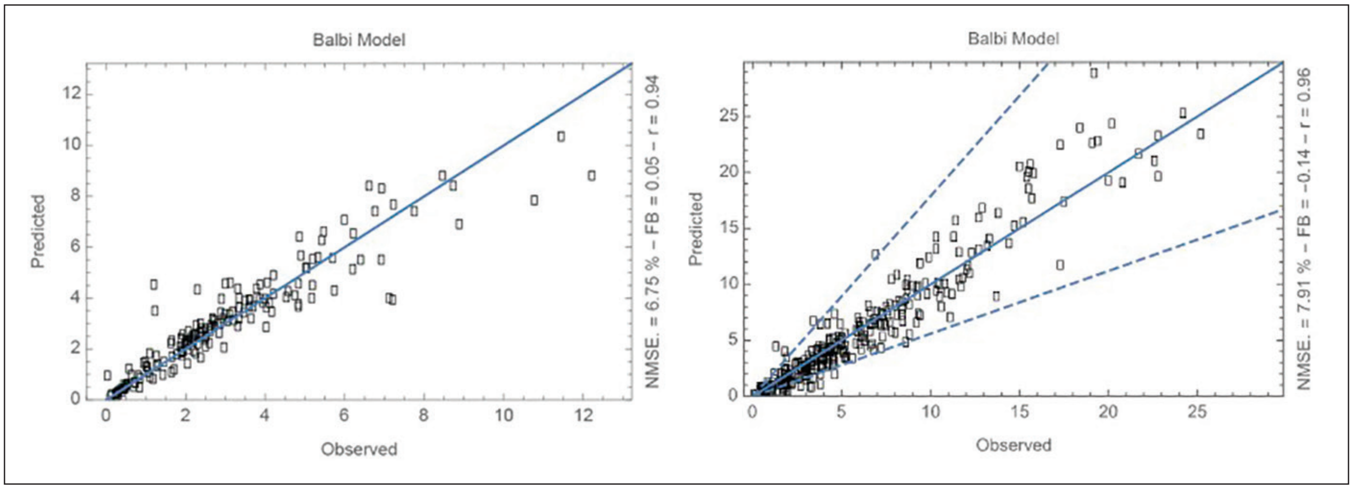


**Figure 1**—Predicted ROS given by the convective model versus observed ROS for the 172 fires spreading in well-ordered and vertically-oriented fuel beds (left) and Predicted ROS given by the radiative convective model vs observed ROS for the 357 fires carried out by Catchpole et al. 1998 (right). NMSE = Normalized Mean Square Error, FB = Fractional Bias, *r* = Pearson's correlation coefficient.

Bias close to zero and the Pearson's correlation coefficient close to Unity. But the most important thing is that the model has no model parameters. The only changing characteristics from one experiment to another are wind velocity, terrain slope angle and fuel characteristics.

## 2017—The Radiative-Convective Model

The combination of the convective and radiative models allows us to obtain a complete model. Note that the radiative model was improved with the removal of all the model parameters. The ROS is an increasing function of the wind velocity. After a fast increase, the ROS reaches a plateau which is obtained for a threshold value of the wind speed. Below this value, we can say that flame radiation is negligible. Above this value, the competition between flame radiation and convection involves a negligible flame base radiation.

The main equation of the model is the following definition of the rate of spread:

$$R = R_b + R_f + R_c = R_b + A\,R\,\frac{1+\sin\gamma-\cos\gamma}{1+\frac{R\cos\gamma}{r_0}} + b\,U\,e^{-K\,R} \quad (3)$$

where $R_f$ is the flame radiation, $R_c$ is the convective effects, $K$ is a drag forces coefficient and $b$ is a convective coefficient which depends on fuel characteristics.

This complete model was confronted to the 357 laboratory fires carried out by Catchpole et al. (1998). We can observe (fig. 1, right) a small error (less than 8%) a light underestimation and a Pearson's correlation coefficient close to Unity.

## 2018—The Field Scale Model

This year, we confronted our model to the field scale. When the fuel bed is a homogeneous vegetal stratum, the model gives very good results (see fig. 2, left, for the results on the fires performed by Gould 1991). But when the vegetal stratum is composed of dead and living particles, we need to make a new assumption. Indeed, the dead part of the fuel is the mainspring of the spread, whereas the living part of the fuel acts as a brake for the spread. So convection will be changed in this case. Actually, in order for the living part of the fuel to be dried out and pyrolyzed, a flame must exist in the base. So, this new following assumption is made with no convection in case of flame depth ($e_c$) equal to zero:

$$R_c = \begin{cases} 0 & if\ e < e_c \\ b\,U\,e^{-K\,R}\left(1-\frac{e_c}{e}\right) & if\ e \geq e_c \end{cases} \quad (4)$$

where $e$ is the fuel thickness and $e_c$ is the depth of the flame into the flame base.

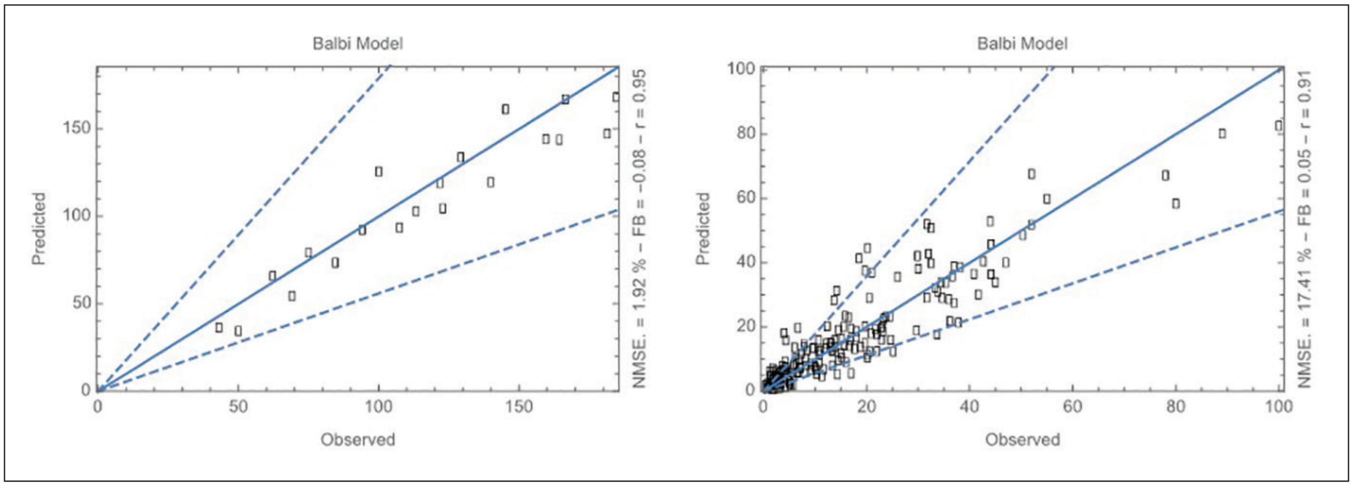


**Figure 2**—Predicted ROS given by the field scale model versus observed ROS for the fires performed by Gould 1991 (left) and sets of field scale experiments (193 fires), mainly shrublands and grasslands (right).

This field scale model was applied to almost 200 fires (mainly shrubland and grassland fires) and the results are encouraging (see fig. 2, right) with an error below the 20 percent level and a good correlation.

## CONCLUSION

Ten years ago, we started with a simplified semi-physical surface fire propagation model with many weaknesses and we finished with a simplified physical model which takes into account radiation and convection and, above all, without any model parameters.

The radiant coefficient is an example of this work: from a fitted parameter, it gained a physical meaning. Obviously, taking convection into account and the removal of all the model parameters (thanks to physical modeling) are the two major improvements.

The radiative-convective model has been confronted to several fires with an average error of 8 percent at the laboratory scale and about 20 percent at the field scale.

## REFERENCES


Balbi, J.H.; Rossi, J.L.; Marcelli, T.; Santoni, P.A. 2007. A 3D physical real-time model of surface fires across fuel beds. Combustion Science and Technology. 179(12): 2511–2537.

Balbi, J.H.; Morandini, F.; Silvani, X.; Filippi, J.B.; Rinieri, F. 2009. A physical model for wildland fires. Combustion and Flame. 156: 2217–2230.

Balbi, J.H.; Rossi, J.L.; Marcelli, T.; Chatelon, F.J. 2010. Physical modeling of surface fire under nonparallel wind and slope conditions. Combustion Science and Technology. 182: 922–939.

Balbi, J.H.; Viegas, D.X.; Rossi, J.L.; Rossa, C.; Chatelon, F.J.; Cancellieri, D.; Simeoni, A.; Marcelli, T. 2014a. Surface fires: no wind, no slope, marginal burning. Journal of Environmental Science and Engineering A. 3: 73–86.

Balbi, J.H.; Chatelon, F.J.; Rossi, J.L.; Simeoni, A.; Viegas, D.X.; Rossa, C. 2014b. Modelling of eruptive fire occurrence and behavior. Journal of Environmental Science and Engineering B. 3: 115–132.

Catchpole,W.R.; Catchpole, E.A.; Butler, B.W.; Rothermel, R.C.; Morris, G.A.; Latham, D.J. 1998. Rate of spread of free-burning fires in woody fuels in a wind tunnel. Combustion Science and Technology. 131: 1–37.

Chatelon, F.J.; Balbi, J.H.; Morvan, D.; Rossi, J.L.; Marcelli, T. 2017. A convective model for laboratory fires with well-ordered vertically-oriented fuel beds. Fire Safety Journal. 90: 54–61.

Finney, M.A.; Forthofer, J.; Grenfell, I.C.; Adam, B.A.; Akafuah, N.K., Saito, K. 2013. A study of flame spread in engineered cardboard fuelbeds. Part I: Correlations and observations. In Proceedings of Seventh International Symposium on Scale Modeling. Hirosaki, Japan, Aug 6-9. 11p.

Gould, J.S. 1991. Validation of the Rothermel fire spread model and related fuel parameters in grassland fuels. In: Cheney, N.P.; Gill, A.M., eds. Proceedings of a Conference on Bushfire Modelling and Fire Danger Rating Systems. 11-12 July 1988. Canberra, Australia:CSIRO: 51–64.

Koo, E.; Pagni, P.; Woycheese, J.; Stephens, S.; Weise, D.; Huff, J. 2005. A simple physical model for forest fire spread rate. Fire Safety Science-Proceedings of the Eighth International Symposium: 851–862.

Linn, R.; Winterkamp, J.; Edminster, C.; Colman, J.J.; Smith, W.S. 2007. Couples influences of topography and wind on wildland fire behaviour. International Journal of Wildland Fire. 16: 183–195.

Mell, W.; Charney, J.J.; Jenkins, M.A.; Cheney, P.; Gould, J. 2005. Numerical simulations of grassland fire behaviour from the LANL—FIRETEC and NIST—WFDS models. In: For EastFIRE Conference. Fairfax, VA: George Mason University.

Morvan, D.; Meradji, S.; Accary, G. 2009. Physical modelling of fire spread in grasslands. Fire Safety Journal. 44: 50–61.

Morvan, D. 2014. Wind effects, unsteady behaviors and regimes of propagation of surface fires in open field. Combustion Science and Technology. 186(7): 869–888.

Pagni, P.J.; Peterson, G. 1973. Flame spread through porous fuels. In: Proceedings of 14th Symposium (International) on Combustion. Pittsburgh, PA: The Combustion Institute: 1099–1107.

Rossi, J.L.; Chetehouna, K.; Collin, A.; Moretti, B.; Balbi, J.H. 2010. Simplified flame models and prediction of the thermal radiation emitted by a flame front in an outdoor fire. Combustion Science and Technology. 182: 1457–1477.

Rossi, J.L.; Simeoni, A.; Moretti, B.; Leroy-Cancellieri, V. 2011. An analytical model based on radiative heating for the determination of safety distances for wildland fires. Fire Safety Journal. 46: 520–527.

Rothermel, R.C.; Anderson, H.E. 1996. Fire spread characteristics determined in the laboratory. Res. Paper INT-30. Ogden, UT: USDA Forest Service, Intermountain Forest & Range Experiment Station. 34 p.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Paper INT-115. Ogden, UT: USDA Forest Service, Intermountain Forest & Range Experiment Station. 40 p.

Wolff, M.F.; Carrier, G.F.; Fendell, F.E. 1991. Wind-aided firespread across arrays of discrete fuel elements. II. Experiment. Combustion Science and Technology. 77: 261–289.