



## A FAST METHOD FOR PRELIMINARY EVALUATION OF CHEMICAL EROSION ON A COMPOSITE NOZZLE

Flávia O. Untem<sup>(1)</sup>, Fábio L. Calciolari<sup>(1)</sup>, Luiz E. N. de Almeida<sup>(1)</sup>, Gustavo H. Murari<sup>(1)</sup> and Wagner K. A. Silva<sup>(1)</sup>

(1) Avibras Indústria Aeroespacial S/A, Brazil

<https://doi.org/10.21452/bccm4.2018.09.03>

### Abstract

Most solid rocket motors (SRM) make use of polymeric composites as ablative thermal protection system (TPS). One of the main advantages of this type of cooling is its simplicity and cost; however, the mechanism of erosion on the composite surface is very complex and tricky to model. In the present work, an ablation model was developed considering the reaction of H<sub>2</sub>O and CO<sub>2</sub> molecules, present in the combustion gases, with the ablative material. This approach is valuable for a preliminary assessment of the behaviour of ablative layers. The investigation was based on a particular case of a SRM ablative nozzle since it is a critical setup for this type of thermal protection system. The bisection method was used for 02 particular propellant formulations in order to predict the mass consumption rate of the ablative material in function of the nozzle diameter and the mass fraction of aluminium.

**Keywords:** ablation model, SRM, nozzle, chemical erosion.

### 1. INTRODUCTION

Solid rocket motors nozzles operate in severe conditions of pressure and temperature, so that dimensioning the insulation protection is necessary in order to assure its integrity during the operation time [1]. The use of composite and ablative materials for this type of application is consecrated and it has been used since the 1970s in the aerospace industry [2].

The ablation is a complex phenomenon that may comprehends physical and chemical processes, including heat conduction, pyrolysis, carbonization, thermochemical reactions, mechanical erosion, and others [3]. Figure 1 presents a scheme of the ablation process.

When using charring materials, the thermochemical ablation comprehends the degradation of the material and subsequent formation of a carbonaceous char layer due to the exposure of its surface to high temperature gas flow, and particles at high speed [1].

As the local temperature exceeds the pyrolysis temperature of the material, the degradation starts and the pyrolysis gases are released by diffusion. The endothermic reaction provides the transformation of thermal energy into chemical energy, leading to cleavage of molecular bounds and formation of the char layer, which leads to the reduction of heat flow on the surface [2].

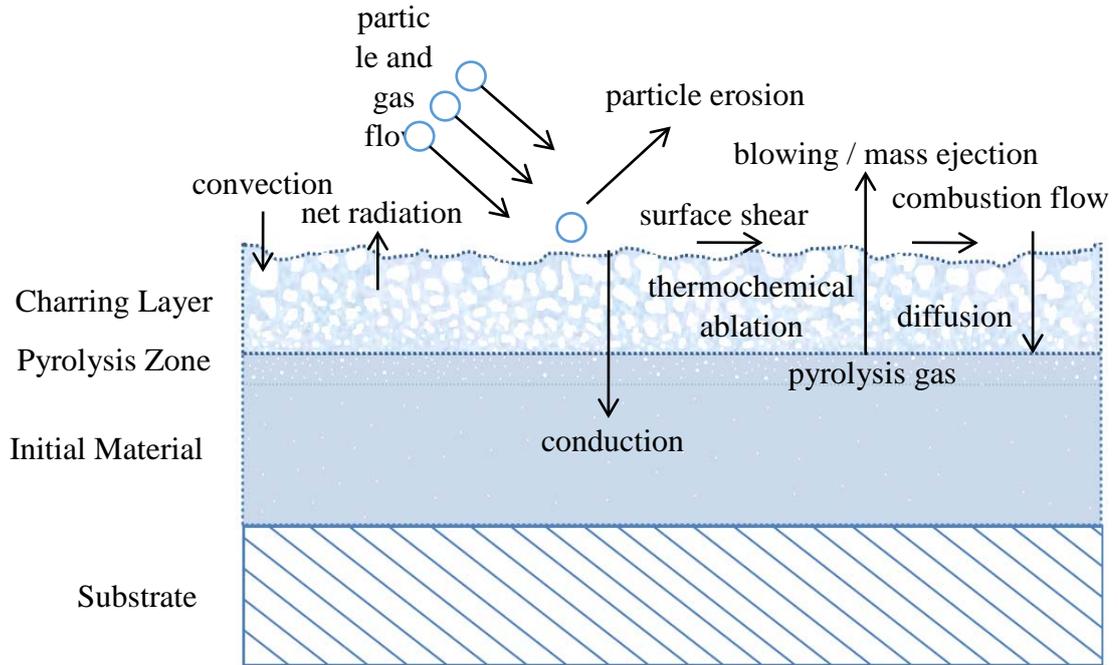


Figure 1: Scheme of ablation process based on [1].

In this context, it is of great interest to predict the efficacy of insulation protection system on a SRM and its behavior during operating time. Several ablation models and computational tools have been developed in order to study the ablation mechanism, with several levels of complexity [3, 4, 5].

Some models consider the ablation as a consequence strictly related to the interaction of combustion gases species with the ablative material surface. This approach disregards other events that contribute to a more intensive recession rate, once it is known that the presence of solid particles contributes to mechanical and thermal erosion of ablative material [6].

Although this kind of model is relatively simple, it can be used for preliminary selection of ablative materials for insulation protection systems, since it is a fast and low cost method [7], being a first step for a subsequent more complex ablation model adoption.

The objective of this work was to propose a fast method to predict the chemical erosion of ablative materials used in thermal protection systems of SRM, relating the material mass consumption rate as function of propellant formulation and project dimensions of the nozzle, assuming that the charred residue is composed only by carbon.

## 2. METHODOLOGY

### 2.1. Thermochemical Ablation Model

The equilibrium composition of the combustion products and their mass fraction were obtained from the computer program NASA –CEA [8]. Among all gases species resulting from the combustion, just CO<sub>2</sub> and H<sub>2</sub>O were considered in the thermochemical ablation model, as they represent the most significant portion of the phenomenon concerned. Thus, the main heterogeneous chemical reactions are represented in Equations (1) and (2):



The thermochemical ablation rate is defined by Equation 3[1][5]:

$$\dot{r} = k_i P_i^n \quad (3)$$

where  $\dot{r}$  is the mass consumption rate of CO<sub>2</sub> and H<sub>2</sub>O in kg/(m<sup>2</sup>.s);  $k_i$  is the reaction rate constant (s/m);  $P_i$  is the partial pressure (Pa) of the reagent, and n is the pressure exponent.

The reaction rate constant ( $k_i$ ) is expressed by the Arrhenius equation defined by:

$$k_i = A_i e^{(-E_i/RT_w)} \quad (4)$$

Where  $A_i$  is the pre exponential factor of the reaction rate (s/m),  $E_i$  is the reaction activation energy (J/mol),  $R$  is the universal gas constant (8.3144 J/mol.K), and  $T_w$  is the wall temperature (K).

The pre exponential factor, the pressure exponent and the activation energies of the chemical reactions described by Equations (1) and (2) were obtained from [1] and [9] and can be seen in Table 1.

Table 1: Pre exponential factor, activation energy and pressure exponent for chemical reactions described by Equations 1 and 2.

Reaction	$A_i$ (kg.m <sup>-2</sup> .s <sup>-1</sup> .Pa <sup>-n</sup> )	$E_i$ (J.kg <sup>-1</sup> )	n
C + CO <sub>2</sub> → 2CO	9.0 x 10 <sup>3</sup>	284,658	0.5
C + H <sub>2</sub> O → H <sub>2</sub> + CO	4.8 x 10 <sup>5</sup>	287,584	0.5

The mass consumption rate of CO<sub>2</sub> and H<sub>2</sub>O were calculated as Equations 5 and 6:

$$\dot{m}_{CO_2} = 9,000 P_{CO_2}^{0.5} e^{(-284,658/RT_w)} \quad (5)$$

$$\dot{m}_{H_2O} = 480,000 P_{H_2O}^{0.5} e^{(-287,584/RT_w)} \quad (6)$$

Finally, Equation 7 expresses the carbon mass consumption rate by thermochemical ablation:

$$\dot{m}_C = \left(\frac{M_C}{M_{CO_2}}\right) \dot{m}_{CO_2} + \left(\frac{M_C}{M_{H_2O}}\right) \dot{m}_{H_2O} \quad (7)$$

where  $\dot{m}_C$  is the carbon mass consumption rate, and  $M_C$ ,  $M_{CO_2}$  and  $M_{H_2O}$  are the molecular mass of C, CO<sub>2</sub>, and H<sub>2</sub>O (12.017 g/mol, 44.01 g/mol, and 18.015 g/mol, respectively).

## 2.2. Evaluation of the nozzle inner wall temperature

To evaluate the inner wall temperature of the nozzle the thermal resistance approach was used. This strategy is justified because despite the outer wall has a very long transient the inner wall rapidly reach the steady state condition [5]. Since the inner surface of the tube suffers a continuous regression, the energy balance in the internal boundary can be expressed as:

$$h_g (T_g - T_w) = -k_s \left. \frac{\partial T}{\partial r} \right|_{r=r_i} + \rho_s \dot{r} \Delta H_r \quad (8)$$

where  $h_g$  is the convective coefficient of the hot gases [W/(m<sup>2</sup>.K)],  $T_g$  is the combustion products static temperature [K],  $T_w$  is the inner wall temperature [K],  $k_s$  is the conductive coefficient of the first layer [W/(m.K)],  $\rho_s$  is the density of the first layer [kg/m<sup>3</sup>],  $\dot{r}$  is the surface progression rate due to chemical erosion [m/s], and  $\Delta H_r$  is the net enthalpy of the reaction of interest [J/kg].

Since steady state conditions are being considered Equation (8) becomes:

$$h_g(T_g - T_w) = -k \frac{\partial T}{\partial r} + \rho_s \dot{r} \Delta H \quad (9)$$

Equation 10 represents the heat flux inside the tube:

$$q_r'' = -k \frac{\partial T}{\partial r} = U(T_w - T_o) \quad (10)$$

where  $T_o$  is the outer wall temperature and:

$$U = \frac{1}{r_1 \sum_{i=1}^N \frac{1}{k_i} \ln \left( \frac{r_{i+1}}{r_i} \right)} \quad (11)$$

The heat flux of the wall can also be expressed as the amount of heat lost to the environment due to natural convection and radiation, so:

$$q_r'' = h_\infty(T_o - T_\infty) + \epsilon \sigma (T_o^4 - T_\infty^4) \quad (12)$$

where  $h_\infty$  is the natural convection coefficient and  $T_\infty$  is the reference temperature. The convective coefficient of the combustion gases passing through the nozzle can be determined by the following [10]:

$$h_g = 0.026k \left( \frac{\rho v}{\mu} \right)^{\frac{4}{5}} \left( \frac{1}{D} \right)^{\frac{1}{5}} \left( \frac{C_p \mu}{k} \right)^{\frac{2}{5}} \quad (13)$$

The convective coefficient on the cold side can be determined with the expression [11]

$$h_\infty = \left( \frac{k}{D} \right) C R a^n \quad (14)$$

where  $R_a$  is the Rayleigh number and the parameters  $C$  and  $n$  are the ones presented in Table 2 [11]:

Table 2: Rayleigh number and the parameters C and n.

Ra	C	n
$10^{-10} - 10^{-2}$	0.675	0.058
$10^{-2} - 10^2$	1.020	0.148
$10^2 - 10^4$	0.850	0.188
$10^4 - 10^7$	0.480	0.250
$10^7 - 10^{12}$	0.125	0.333

Using equations (9) - (14) and knowing that  $T_\infty < T_o < T_g$  the problem can be easily solved by a bisection scheme.

In this work it was considered 2 propellants formulations based on AP/Al/HTPB, named as P1 and P2. The AP content was fixed at 70% and 80% for propellant P1 and P2, respectively, and mass consumption rates were evaluated in function of fraction of aluminium and nozzle diameter for each case.

### 3. RESULTS AND DISCUSSION

The method allowed the estimation of mass consumption rate of ablative materials for a wide range of propellant formulations and nozzle diameter. Figures 2 and 4 present contour

plots for propellant P1 and P2, respectively, wherein each color line corresponds to a specific mass consumption rate

It is possible to notice from Figures 2 and 4 that mass consumption rate of ablative material is directly proportional to mass fraction of Al present in propellant formulation and inversely proportional to nozzle diameter, as expected.

However, when trying to achieve a desired recession rate one must not be restricted by the adjustment of these two parameters only, but the propulsive performance has to be taken into account as well. Figures 3 and 5 present the specific impulse as a function of the mass fraction of Al for propellant P1 and P2, respectively.

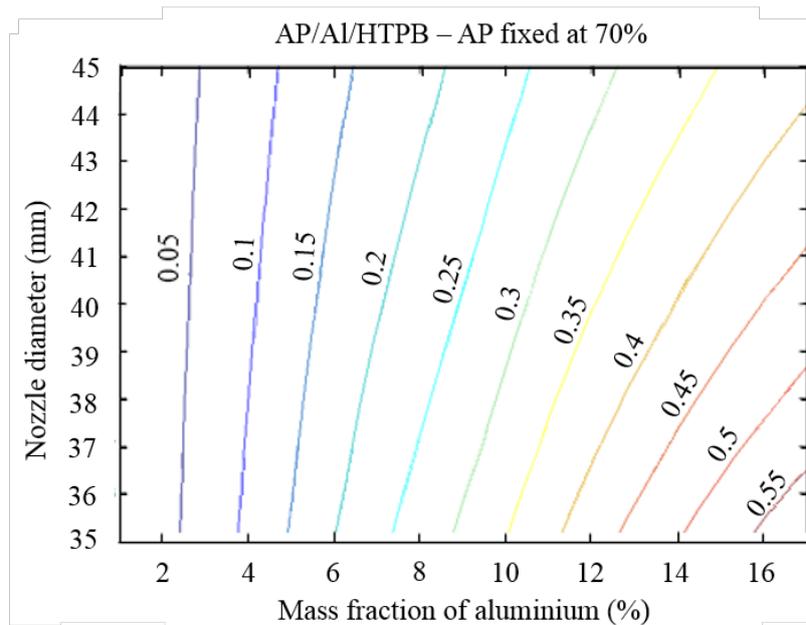


Figure 2: Contour plot for propellant P1

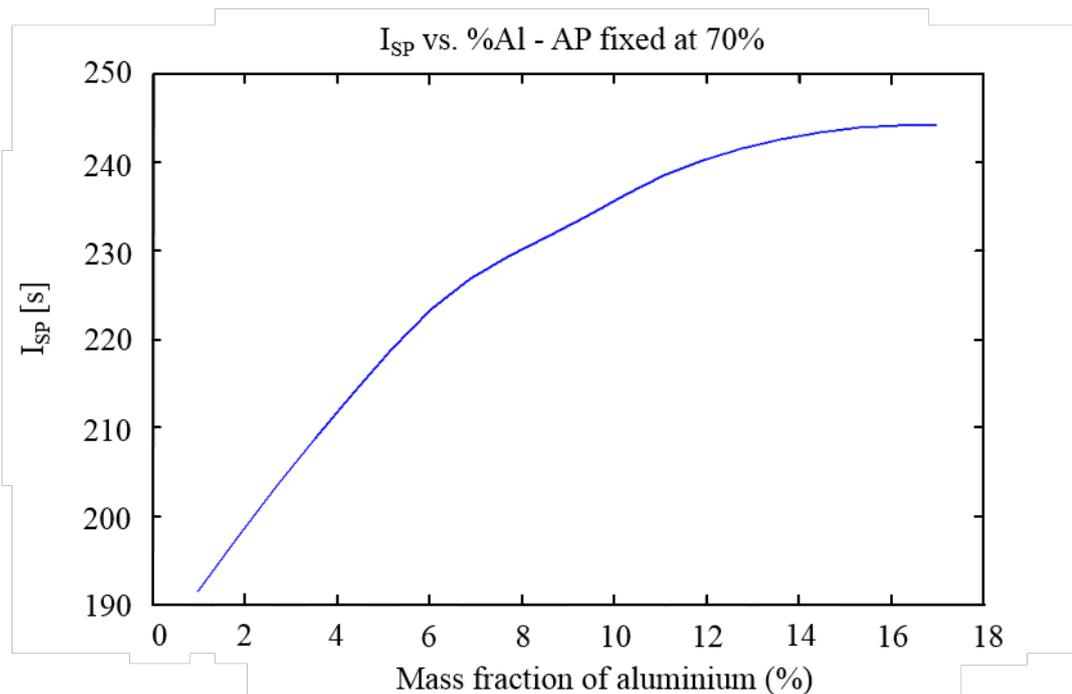


Figure 3: Specific impulse (s) as a function of mass fraction of Aluminium (%) for propellant P1.

From the contour plots, Figures 2 and 4, it can be seen that a design setup with propellant P1 the erosion rate is less sensitive to variations of nozzle diameter compared to one with propellant P2. As a contrast, the setup with propellant P2 is way less sensitive to Al mass fraction variations. The contour plots with the performance plots constitute, thus, a complex map to be used jointly for design decision making.

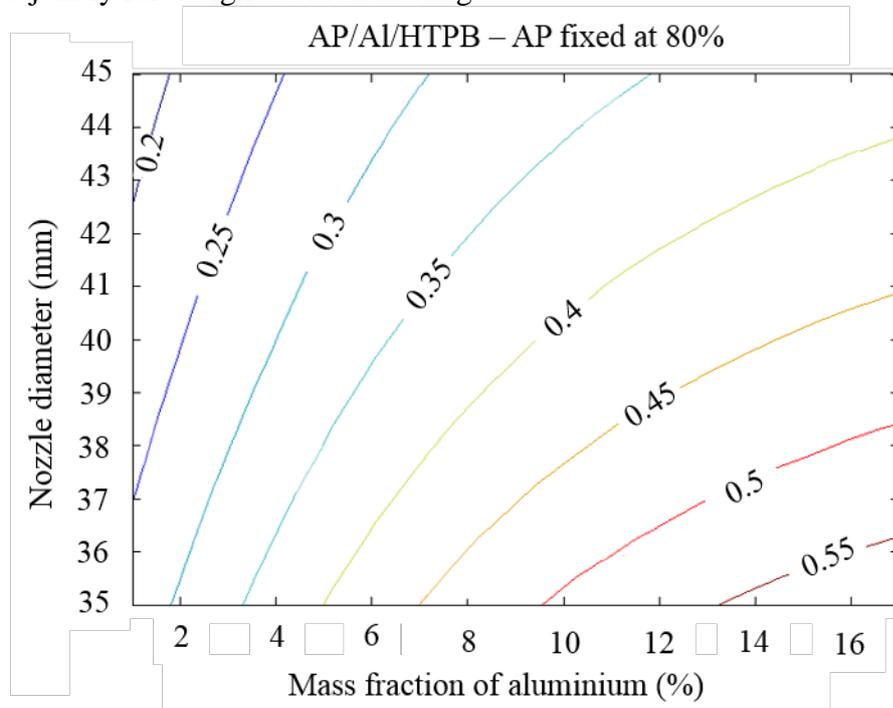


Figure 4: Contour plot for propellant P2.

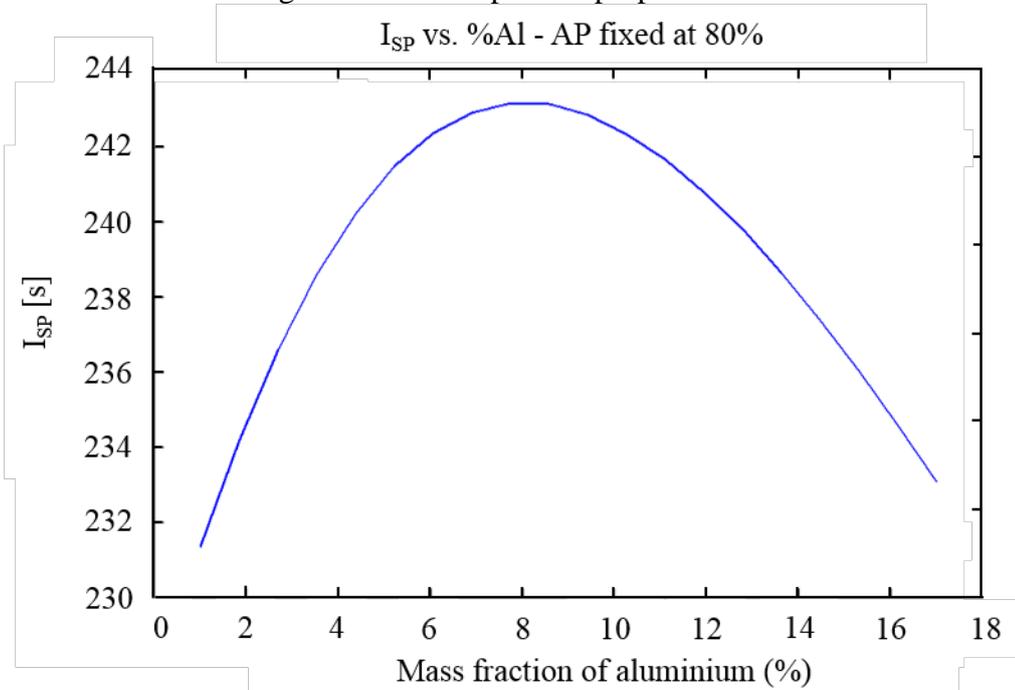


Figure 5: Specific impulse (s) as a function of mass fraction of Aluminium (%) for propellant P2.

## 1. CONCLUSIONS

The proposed method allows quick evaluation of the material behavior in relation to its chemical erosion, making it possible to verify the adequacy of material for such application in a preliminary basis. The contour plot is a valuable tool to comprehend the influence of both nozzle diameter and propellant chemical composition on the erosion rate and can be used along with the SRM propulsive performance plot to make project decisions. Neither the direct correlation among these 3 parameters, nor a methodology to evaluate preliminarily the material selection of TPS are usual in the literature. The selection and dimensioning of TPS materials in early design phase is often based on experience. In this context, one can consider the proposed method as a useful tool in the initial stages of TPS definition, that may be used in a step prior to the use of a more complex ablation model. As a future work, we suggest to perform functional tests that may support the validation of this method as a tool to define thermal protection solutions on early stages of development of SRMs.

## ACKNOWLEDGMENTS

The authors are thankful to AVIBRAS Indústria Aeroespacial for providing the materials used in this study and for allowing partial divulgation of test results.

## REFERENCES

- [1] Xu, Y. H., Hu, X., Yang, Y.X., Zeng, Z.X. and Hu, C.B., 'Dynamic Simulation of Insulation Material Ablation Process in Solid Propellant Rocket Motor', *Journal of Aerospace Engineering*, **28**, (5) (2015).
- [2] Rossi R. C. and Wong, W. C. 'Availability of Aerospace Rayon for SRM Nozzle Insulators', *American Institute of Aeronautics and Astronautics*(1996).
- [3] Liu, Y., Yang, S., He, G. and Li, J. 'An Overall Ablation Model of Ethylene-Propylene-Diene Monomer Based on Porous Characteristics in Char Layer', *Advances in Mechanical Engineering*, **8**(2) (2016) 2-10.
- [4] Machado, H. A. 'Simulation of Ablation in a Composite Thermal Protection System via an Interface Tracking Method', *J. Aerosp. Technol. Manag.* (2012).
- [5] Bianchi, D., Turchi, A., Nasuti, F. and Onofri, M. 'Chemical Erosion of Carbon-Phenolic Rocket Nozzles with Finite-Rate Surface Geometry', *Journal of Propulsion and Power*, **29**(5)(2013).
- [6] Wirzberger H., and Yaniv, S. 'Prediction of Erosion in a Solid Rocket Motor by Alumina Particles', *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*.(2005). 9.
- [7] Li, J., Zhang, M. and Zhang, J. 'Numerical Simulation of Insulation Layer Ablation in Solid Rocket Motor Based on Fluent', *Applied Mechanics and Material*.(574) (2014) 224-22
- [8] Gordon S., and McBride B. J. 'Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications', *National Aeronautics and Space Administration, Office of Management, Scientific and Technical Information Program*. (1994).
- [9] Chelliah, H. K., Makino, A., Kato, I., Araki, N. and Law, C. K. 'Modeling of Graphite Oxidation in a Stagnation-Point Flow Field using Detailed Homogeneous and Semiglobal Heterogeneous Mechanisms With Comparisons to Experiments', *Combust. Flame*, **104** (1996) 469-480
- [10] Humble, R. W., Henry, G. N. and Larson, W. J. 'Space Propulsion Analysis and Design, McGraw-Hill'.(1995).
- [11] Bergman, T. L., Lavine, A. S., Incropera, F. P. and Dewitt, D. P. 'Fundamentals of Heat and Mass Transfer', 7th Edn (John Wiley & Sons, 2011).