

# Case Study: Ablation of CFRP Laminated Composite – Ablation Rate

□ The ablation rate is assumed to follow Park's finite-rate ablation formulation [3-5], the mass blowing rates, m, due to various surface-gas reactions (i.e., oxidation, nitridation, and sublimation) are:

$$n = \rho_e C_o \overline{v}_o \beta_o \frac{M_C}{M_O}; \quad (C_{(S)} + O \rightarrow CO), \quad n = 2\rho_e C_{O_2} \overline{v}_{O_2} \beta_{O_2} \frac{M_C}{M_{O_2}}; \quad (2C_{(S)} + O_2 \rightarrow 2CO), \quad n = 2\rho_e C_{O_2} \overline{v}_{O_2} \beta_{O_2} \frac{M_C}{M_{O_2}}; \quad (2C_{(S)} + O_2 \rightarrow 2CO), \quad n = 2\rho_e C_{O_2} \overline{v}_{O_2} \beta_{O_2} \frac{M_C}{M_{O_2}}; \quad (2C_{(S)} + O_2 \rightarrow 2CO), \quad n = 2\rho_e C_{O_2} \overline{v}_{O_2} \beta_{O_2} \frac{M_C}{M_{O_2}}; \quad (2C_{(S)} + O_2 \rightarrow 2CO), \quad n = 2\rho_e C_{O_2} \overline{v}_{O_2} \beta_{O_2} \frac{M_C}{M_{O_2}}; \quad (2C_{(S)} + O_2 \rightarrow 2CO), \quad n = 2\rho_e C_{O_2} \overline{v}_{O_2} \beta_{O_2} \frac{M_C}{M_{O_2}}; \quad (2C_{(S)} + O_2 \rightarrow 2CO), \quad n = 2\rho_e C_{O_2} \overline{v}_{O_2} \beta_{O_2} \frac{M_C}{M_{O_2}}; \quad (2C_{(S)} + O_2 \rightarrow 2CO), \quad n = 2\rho_e C_{O_2} \overline{v}_{O_2} \beta_{O_2} \frac{M_C}{M_{O_2}}; \quad (2C_{(S)} + O_2 \rightarrow 2CO), \quad n = 2\rho_e C_{O_2} \overline{v}_{O_2} \beta_{O_2} \frac{M_C}{M_{O_2}}; \quad (2C_{(S)} + O_2 \rightarrow 2CO), \quad n = 2\rho_e C_{O_2} \overline{v}_{O_2} \beta_{O_2} \frac{M_C}{M_{O_2}}; \quad (2C_{(S)} + O_2 \rightarrow 2CO), \quad n = 2\rho_e C_{O_2} \overline{v}_{O_2} \beta_{O_2} \frac{M_C}{M_{O_2}}; \quad (2C_{(S)} + O_2 \rightarrow 2CO), \quad n = 2\rho_e C_{O_2} \overline{v}_{O_2} \beta_{O_2} \frac{M_C}{M_{O_2}}; \quad (2C_{(S)} + O_2 \rightarrow 2CO), \quad n = 2\rho_e C_{O_2} \overline{v}_{O_2} \beta_{O_2} \frac{M_C}{M_{O_2}}; \quad (2C_{(S)} + O_2 \rightarrow 2CO), \quad n = 2\rho_e C_{O_2} \overline{v}_{O_2} \beta_{O_2} \frac{M_C}{M_{O_2}}; \quad (2C_{(S)} + O_2 \rightarrow 2CO), \quad n = 2\rho_e C_{O_2} \overline{v}_{O_2} \beta_{O_2} \frac{M_C}{M_{O_2}}; \quad (2C_{(S)} + O_2 \rightarrow 2CO), \quad n = 2\rho_e C_{O_2} \overline{v}_{O_2} \beta_{O_2} \frac{M_C}{M_{O_2}}; \quad (2C_{(S)} + O_2 \rightarrow 2CO), \quad n = 2\rho_e C_{O_2} \overline{v}_{O_2} \beta_{O_2} \frac{M_C}{M_O_2}; \quad (2C_{(S)} + O_2 \rightarrow 2CO), \quad n = 2\rho_e C_{O_2} \overline{v}_{O_2} \beta_{O_2} \frac{M_C}{M_O_2}; \quad (2C_{(S)} + O_2 \rightarrow 2CO), \quad (2C_{(S)}$$

$$n\delta \xi = \rho_e C_N \overline{v}_N \beta_N \frac{M_C}{M_V}; \quad \left(C_{(S)} + N \rightarrow CN\right), \quad n\delta \xi = \rho_e \left(C_{C_3,E} - C_{C_3}\right) \overline{v}_{C_3} \beta_{C_3}; \quad \left(3C_{(S)} \rightarrow C_3\right),$$

$$n\delta \xi = n\delta \xi + n\delta \xi + n\delta \xi + n\delta \xi + n\delta \xi$$
,  $n\delta \xi = 0.21n\delta \xi$ ,  $s\delta = \left(n\delta \xi + n\delta \xi\right)/\rho_s$ ,

Such a formulation may be <u>inappropriate</u> to model ablation under radiative heating environment. The case study does not necessarily reflect the real physics, but should be regarded as a demonstration of the modeling capability of this proposed MMM procedure.

<sup>[3]</sup> C. Park, Stagnation-point ablation of carbonaceous flat disks. I theory, AIAA Journal, 21 (11) (1983) 1588-1594.

<sup>[4]</sup> C. Park, Calculation of stagnation-point heating rates associated with stardust vehicle, Journal of Spacecraft and Rockets, 41 (1) (2007) 24-32.

<sup>[5]</sup> C. Park, H.K. Ahn, Stagnation-point heat transfer rates for pioneer-venus probes, Journal of Thermophysics and Heat Transfer, 13 (1) (1999) 33-41.

# **Moving Finite Elements**

J. D. P. Donnelly,Oxford University Computing Laboratory. Numerical Analysis Group

#### **Moving Finite Elements:**

Moving Finite Elements in 2-D. Robert J. Gelinas, SCIENCE APPLICATIONS INC PLEASANTON CALIF., 1981 The moving finite element MFE method is a new PDE solution method which has shown significant promise in 1 D for the numerical solution of some of the most difficult problems under study with extremely large but finite gradients The overall objective of the present research is to explore further the promise of the continuous node moving properties of the MFE method in 2 D For this both the logical structure of the MFE method and its reduction to practice in 2 D are under investigation in this project This initial research in 2 D focuses upon such simple conservation equations as heat travelling wave and Burger's equations Work in this initial reporting period has resulted in significant computational economies for both unvectorized versions of the MFE method as it currently exists and for vectorized versions which may emerge in later efforts A working test code which is needed for essential scientific exploration and further enhancement of the MFE method in higher dimensions has been brought to nearly an operational stage of execution during this period Author Finite Element Method Maria do Carmo Coimbra, Alirio Egidio Rodrigues, Jaime Duarte Rodrigues, Rui Jorge Mendes Robalo, Rui Manuel Pires Almeida, 2016-11-30 This book focuses on process simulation in chemical engineering with a numerical algorithm based on the moving finite element method MFEM It offers new tools and approaches for modeling and simulating time dependent problems with moving fronts and with moving boundaries described by time dependent convection reaction diffusion partial differential equations in one or two dimensional space domains It provides a comprehensive account of the development of the moving finite element method describing and analyzing the theoretical and practical aspects of the MFEM for models in 1D 1D 1d and 2D space domains Mathematical models are universal and the book reviews successful applications of MFEM to solve engineering problems It covers a broad range of application algorithm to engineering problems namely on separation and reaction processes presenting and discussing relevant numerical applications of the moving finite element method derived from real world process simulations Moving Finite Elements: Regularisation Techniques M. J. Baines, 1986 Moving Finite Element Method Maria do Carmo Coimbra, Alirio Egidio Rodrigues, Jaime Duarte Rodrigues, Rui Jorge Mendes Robalo, Rui Manuel Pires Almeida, 2016-11-30 This book focuses on process simulation in chemical engineering with a numerical algorithm based on the moving finite element method MFEM It offers new tools and approaches for modeling and simulating time dependent problems with moving fronts and with moving boundaries described by time dependent convection reaction diffusion partial differential equations in one or two dimensional space domains It provides a comprehensive account of the development of the moving finite element method describing and analyzing the theoretical and practical aspects of the MFEM for models in 1D 1D 1d and 2D space domains Mathematical models are universal and the book reviews successful applications of MFEM to solve engineering problems It covers a broad range of application algorithm to engineering problems namely on separation and reaction processes

presenting and discussing relevant numerical applications of the moving finite element method derived from real world Moving Finite Elements Michael John Baines, Professor in Applied Mathematics M J Baines, 1994 This process simulations book is mainly concerned with finite element methods for time dependent partial differential equations when the grids are allowed to move in time but also describes grid generation techniques which include grid adjustment The mechanism for grid movement derives from a generalization of the residual minimization technique which is familiar from the Galerkin finite element method The book brings together most of the work done over the last decade or so which has been stimulated by Miller's original idea and discusses the interrelationships between the techniques of the method and the established ideas of the method of characteristics Hamilton's equations the Legendre transformation and grid equidistribution The book highlights the issues involved and should provide the reader with a clear view of the current state of the subject and prompt Local Moving Finite Elements M. J. Baines, 1985 Mesh Free Methods G.R. Liu, 2002-07-29 As we attempt to solve engineering problems of ever increasing complexity so must we develop and learn new methods for doing so The Finite Difference Method used for centuries eventually gave way to Finite Element Methods FEM which better met the demands for flexibility effectiveness and accuracy in problems involving complex geometry Now Moving Finite Elements in 2-D -- Fluid Dynamics Applications, 1984 This report summarizes progress on the feasibility of using the moving finite element MFE method in two dimensional for the study of shock boundary layer interactions It is found that highly local physical dissipation processes in regions of large gradients can be sensitive determinates of macroscopic flow properties. The MFE method continues to show promise for resolving such physical effects while suppressing anomalous or numerical diffusion effects over highly disparate physical scales Recommendations are given for improving the MFE method for further reduction to practice for airblast applications Keywords Viscous Dissipation Implicit Solutions Partial Differential Equation **Navier Stokes Equations** Moving Finite Elements M. J. Baines, 1985 **Moving Finite Element Solution of Systems** of Partial Differential Equations in 1-dimension Mohammad Dhjahed Djomehri,1983 *Applications of the Moving* Finite Element Method for Systems in 2-D. Science Applications International Corporation, M. J. Djomehri, S. K. Doss, R. J. Gelinas, K. Miller, 1985 An Implementation of a Moving Finite Element Method Andrew N. Hryamk, Gregory J. Some Exact Solutions in Moving Finite Elements J. D. P. Donnelly, Oxford McRae, Arthur W. Westerberg, 1984 University Computing Laboratory. Numerical Analysis Group, 1993 A Moving Finite Element Method for Time Dependent Partial Differential Equations with Error Estimation and Refinement S. Adjerid, J. E. Flaherty, RENSSELAER POLYTECHNIC INST TROY NY DEPT OF MATHEMATICAL SCIENCES., 1984 The authors discuss a moving finite element method for solving vector systems of time dependent partial differential equations in one space dimension. The mesh is moved so as to equidistribute the spatial component of the discretization error in H1 They present a method of estimating this error by using p hierarchic finite elements The error estimate is also used in an adaptive mesh refinement procedure to give an algorithm

that combines mesh movement and refinement The authors discretize the partial differential equations in space using a Galerkin procedure with piecewise linear elements to approximate the solution and quadratic elements to estimate the error A system of ordinary differential equations for mesh velocities are used to control element motions. The authors use existing software for stiff ordinary differential equations for the temporal integration of the solution the error estimate and the mesh motion Computational results using a code based on this method are presented for several examples **Elements and Overturning Solutions** Carol Patricia Reeves, 1991 The Moving Finite Element Method for the Viscous Burgers' Equation I. W. Johnson, 1984 Mathematical Methods for the Magnetohydrodynamics of Liquid Metals Jean-Frédéric Gerbeau, Claude Le Bris, Tony Lelièvre, 2006-08-31 This comprehensive text focuses on mathematical and numerical techniques for the simulation of magnetohydrodynamic phenomena with an emphasis laid on the magnetohydrodynamics of liquid metals and on a prototypical industrial application Aimed at research mathematicians engineers and physicists as well as those working in industry and starting from a good understanding of the physics at play the approach is a highly mathematical one based on the rigorous analysis of the equations at hand and a solid numerical analysis to found the simulations At each stage of the exposition examples of numerical simulations are provided first on academic test cases to illustrate the approach next on benchmarks well documented in the professional literature and finally whenever possible on real industrial cases The Moving Finite Element Method for Solving Partial Differential Equations Sohail Aslam, 1985 <u>Uncoupled moving finite elements</u> Richard Lane Thrasher,1989 31st European Symposium on Computer Aided Process Engineering Metin Türkay, Rafiqul Gani, 2021-07-22 The 31st European Symposium on Computer Aided Process Engineering ESCAPE 31 Volume 50 contains the papers presented at the 31st European Symposium of Computer Aided Process Engineering ESCAPE event held in Istanbul Turkey It is a valuable resource for chemical engineers chemical process engineers researchers in industry and academia students and consultants in the chemical industries Presents findings and discussions from the 31st European Symposium of Computer Aided Process Engineering ESCAPE event

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