Plasma Chem Plasma Process (2016) 36:731–736
DOI 10.1007/s11090-016-9706-5

OBITUARY

In Memoriam: Emil Pfender (1925–2016) Professor Emeritus University of Minnesota

Maher Boulos[1] · Pierre Fauchais[2]

The international plasma chemistry community mourns the passing, on January 28th 2016, of Emil Pfender, Emeritus Professor at the University of Minnesota, after a brief illness. Professor Pfender was a leading member of our community and contributed immensely to the understanding of the scientific foundations of this rapidly developing field. He became a Fellow of the American Society of Mechanical Engineers in 1981 and member of the US National Academy of Engineering in 1986. Professor Pfender was recipient of many well-deserved honors from leading scientific societies, including the Alexander von Humboldt Award of the German Government (1978), the Gold Honorary F. Krizik Medal for Merit in

✉ Maher Boulos
Maher.Boulos@tekna.com

[1] Department of Chemical Engineering, University of Sherbrooke, Sherbrooke, QC, Canada

[2] European Center of Ceramics, University of Limoges, Limoges, France

the Field of Technical Sciences of the Czech Academy of Sciences, and an Honorary Doctorate from the Technical University of Ilmenau, Germany. In 1995 he was the first recipient of the Plasma Chemistry Award, then given by the International Union of Pure and Applied Chemistry, and subsequently awarded by the International Plasma Chemistry Society after its founding in 2000. The award, given to a single individual once every 2 years, remains the highest award of the Society, for lifetime achievement in plasma chemistry.

Emil Pfender was born May 25th 1925, in Dietershausen, a small farming village in southern Germany. He earned his Diploma in Physics in 1953, and Dr. Ing. in Electrical Engineering in 1959, both from the Technical University of Stuttgart, where he became Chief Assistant and Lecturer at the Institute for Gaseous Electronics. In 1961 he spent a year as Visiting Scientist at the Plasma Physics Branch of the Air Force Research Laboratories at Wright Patterson Air Force Base, near Dayton, Ohio. In 1964 Professor Pfender was recruited to direct the High Temperature Laboratory (now the High Temperature and Plasma Laboratory), in the Department of Mechanical Engineering at the University of Minnesota. He joined the Department as an Associate Professor, and became Professor in 1967. Under his leadership the HTL (HTPL) grew to become one of the world leading centers in the field of plasma science and technology, with four faculty members and over 20 graduate students and research assistants as well as several postdocs and visiting scientists. The University of Minnesota awarded Professor Pfender a Distinguished Alumni Professorship in 1989 and the Ernst Eckert Professorship in 1994. He formally retired from the University in 2000, but as an Emeritus Professor he remained up to the time of his death an active member of the Graduate Faculty in Mechanical Engineering, co-advising several Ph.D. students.

As colleagues and friends who had the pleasure and privilege of working closely with Emil for more than four decades since the 1970s, we would like to share with the plasma chemistry community our thoughts and fond memories of this period and point out the importance of his contribution to the advancement of our knowledge in plasma chemistry. Emil Pender's contribution can be found in four distinct areas.

- Fundamental research into fluid dynamics and heat transfer under plasma conditions using direct current (DC) and radio frequency (RF) inductively coupled plasma sources. The topics extensively studied by Emil varied widely from electrode phenomena, DC torch design, for plasma spraying and cutting, modelling and diagnostics, to thermal spray coatings applications, chemical vapor deposition and nanopowder synthesis.
- Training of young scientists who completed their Masters and Ph.D. degrees in this field under his supervision, and for whom he has been a lifetime mentor. He was also an active participant in a large number of continuing education courses which we offered together for many years (1981–2001) in conjunction with the annual International Thermal Spray Conferences (ITSC), and the biannual International Symposium on Plasma Chemistry (ISPC).
- Consulting and engineering services to the industrial community on an international scale, contributing to the advancement of the integration of thermal plasmas in their process technology. These were offered either individually or through our joint 'International Thermal Plasma Engineering', a Minnesota corporation that was active in this field over the period 1983–1995.

- In 1980, together with Professor Stan Veprek, then of the University of Zürich, Professor Pfender co-founded the journal *Plasma Chemistry and Plasma Processing*, and served for 25 years as its co-Editor-in-Chief. The journal, now in its 37th year, remains one of the most important in its field.

Professor Pfender worked primarily in the area of thermal plasmas, with particular emphases on plasma heat transfer and plasma processing of materials. He conducted pioneering studies on anode heat transfer in electric arcs. His 1967 publication, together with Ernst Eckert, of "Advances in Plasma Heat Transfer" in *Advances in Heat Transfer*, became a fundamental and frequently cited reference in this area.

In terms of technical achievements, it is indeed a challenging task to attempt to point out a single or specific accomplishment, since Emil devoted his research career to a vast number of diverse topics to which he made significant contributions. Professor Pfender also performed extensive studies of plasma synthesis of ultrafine powders, later termed "nanoparticles", developed processes for using thermal plasmas to deposit thin films and coatings of diamond, and conducted extensive research on plasma spraying to apply protective coatings to surfaces, for applications ranging from jet engine turbine blades to hip implants. The proposed model for the entrainment of cold gas into thermal plasma jets used by the thermal spray industry, had a significant impact on this field. The schematic given in Fig. 1 by Pfender et al. [25], identifying the main regions of transitional plasma jets, has been one of the most cited references on this topic.

It is important to point out that this publication has been the basis of a broad range of subsequent studies in this field, including mixing in plasmas and low density jets by Russ et al. [30], unsteadiness and mixing in thermal plasma jets, by Russ et al. [31] and a two-fluid model of turbulence for a thermal plasma jet, by Huang et al. [16]. Such developments were based on a systematic rigorous approach involving both mathematical

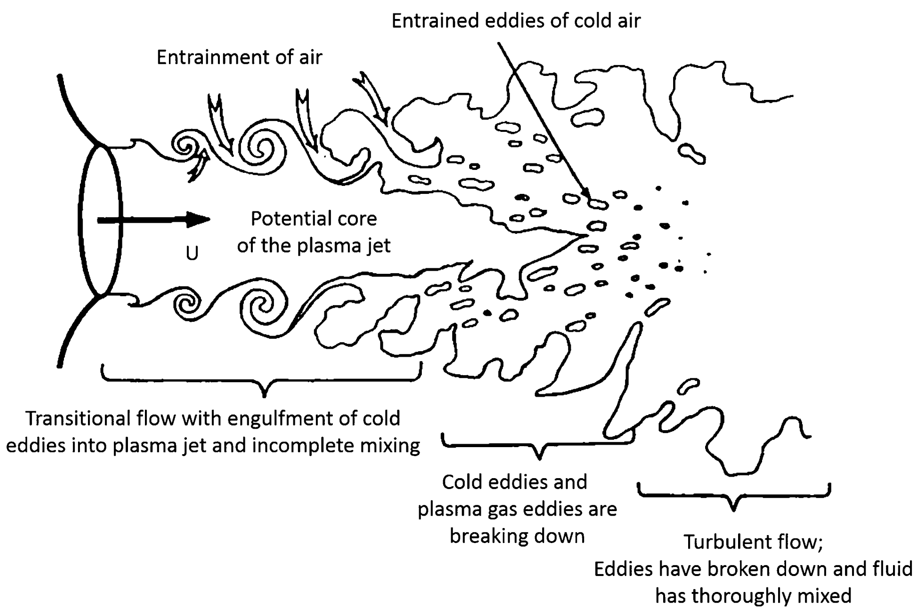

Fig. 1 Main regions of transitional plasma jets, after Pfender et al. [25]

modelling (Chyou et al. 1989) [4–6] and diagnostic tools such as emission spectroscopy and enthalpy probe techniques [2–5, 9]. It is important to underline that, jointly with Professor Joachim Heberlein, Professor Pfender was among the first to simulate dynamics of the arc inside a DC plasma torch, using a three-dimensional, transient, local thermodynamic equilibrium mathematical model with a variational multi-scale numerical approach. Such a model was able to predict the operation of the torch in steady and takeover modes, without any further assumption on the reattachment process except for the use of an artificially high electrical conductivity near the electrodes. Subsequently-developed two-temperature models, with the thermodynamic and transport properties calculated accordingly, also took into account the radiative emission, especially when metal evaporation (from electrodes or treated materials) occurs.

Such studies, while contributing immensely to the advancement of our fundamental understanding of plasmas, also allowed for the improvement of plasma torch designs through the use of vortex gas injection, stabilization of the arc root position, and entrainment of cold surrounding gas in the plasma jet and its impact on the cooling of the plasma jet. Emil has also developed a plasma reactor with a triple-cathode arrangement, allowing for the introduction of a centrally-blown gas stream above the three cathode tips augmenting the regular cathode jets, and allowing for longer stable arcs to be drawn with diffuse anode arc attachments. At the same time, anode heat transfer was substantially increased. He also developed a transferred arc plasma reactor with a converging wall and flow through a hollow cathode, a counter-flow liquid injection torch for the synthesis of spinel powders, and improved conventional spray torches to increase the plasma spraying efficiency and coating quality.

Professor Pfender devoted a significant part of his research efforts to the study of the thermodynamic, transport and radiative properties of plasmas under a wide range of conditions [1, 10, 15, 17, 21–23, 33]. He showed that multicomponent transport determines the actual outcome of many thermal plasma processing techniques. Its proper description requires separate continuity equations for each species, and these equations contain diffusional fluxes for which constitutive relations are needed.

As part of his involvement in the area of thermal spray and the synthesis of advanced materials, Professor Pfender conducted an extensive research program during the 1970s and 1980s dedicated to the study of plasma–particle momentum and heat transfer [7, 8, 13, 14, 18–20, 26, 29, 34, 35]. Among his numerous contributions in this field, Professor Pfender was among the first, if not the first, to point out the challenges linked to the study of the motion of small particles (<10 μm) in plasmas, where the Knudsen effect is of critical importance.

On a more personal note, the three of us shared the strong convection of the important role played by textbook publications to ensure the transfer of knowledge acquired to future generations and newcomers in the field. Bases on the material compiled for our numerous continuing education courses, we embarked in the early eighties on a project for the publication of a textbook entitled *Thermal Plasmas, Fundamentals and Applications*. The first volume of this book was published by Plenum Press in 1994. The preparation of the second volume of this book took too long to materialize, and when it was decided to send it to the press, it was obvious that a new format was needed, which took the shape of a *Handbook of Thermal Plasmas* to be published by Springer in 2017. This Handbook represent an updated version of Vol. 1 of our first book, and the remaining material on plasma science and applications. Progress with this new project was going on well and according to schedule with the first chapters of this 35-chapter handbook already published by Springer on-line. It is unfortunate that Emil left us too early to see the fruit of our joint work completed. Our resolve and commitment to complete what we started together remains strong and we will see to it that it is completed on schedule in his honor.

To conclude, very few university professors have had the influence of Emil Pfender on the fundamental science of thermal plasmas and their applications, especially on torch design optimization, plasma-sprayed coatings and the synthesis of advanced materials. All of us who had the chance to know him will always cherish the fond memory of these moments. Through his publications, students and colleagues, his works on thermal plasmas will continue to guide us in this field.

References

1. Boffa C, Heberlein J, Pfender E (1971) Criterion for establishing deviations from the local thermodynamic equilibrium in atmospheric pressure plasma jets. Wärme und Stoffübertragung 4:S213–S221
2. Brossa M, Pfender E (1988) Probe measurements in thermal plasma jets. Plasma Chem Plasma Process 8(1):75–90
3. Capetti A, Pfender E (1989) Probe measurements in argon plasma jets operated in ambient argon. Plasma Chem Plasma Process 9(2):329–341
4. Chang CH, Pfender E (1990) Non-equilibrium modeling of low-pressure argon plasma jets; part I laminar flow. Plasma Chem Plasma Process 10(3):473–491
5. Chang CH, Pfender E (1990) Non-equilibrium modeling of low-pressure argon plasma jets; part II turbulent flow. Plasma Chem Plasma Process 10(3):493–500
6. Chang CH, Pfender E (1996) Advances in the computational modeling of thermal-plasma processing, JOM June 46–48
7. Chen X, Pfender E (1982) Heat transfer to a single particle exposed to a thermal plasma. Plasma Chem Plasma Process 2(2):185–212
8. Chen X, Chyou YP, Lee YC, Pfender E (1985) Heat transfer to a particle under plasma conditions with vapor contamination from the particle. Plasma Chem Plasma Process 5(2):119–141
9. Chen WLT, Heberlein J, Pfender E (1994) Diagnostics of a thermal plasma jet by optical emission spectroscopy and enthalpy probe measurements. Plasma Chem Plasma Process 14(3):317–332
10. Chen WLT, Heberlein J, Pfender E (1996) Critical analysis of viscosity data of thermal argon plasmas at atmospheric pressure. Plasma Chem Plasma Process 16(4):635–650
11. Chen HC, Pfender E, Heberlein J (1997) Improvement of plasma spraying efficiency and coating quality. Plasma Chem Plasma Process 17(1):93–105
12. Chen HC, Pfender E, Dzur B, Nutsch G (2000) Microstructural characterization of radio frequency and direct current plasma-sprayed Al_2O_3 coatings. J Therm Spray Technol 9(2):264–273
13. Chyou YP, Pfender E (1989) Modeling of plasma jets with superimposed vortex flow. Plasma Chem Plasma Process 9(2):291–328
14. Chyou YP, Pfender E (1989) Behavior of particulates in thermal plasma flows. Plasma Chem Plasma Process 9(1):45–71
15. Ghorui S, Heberlein JVR, Pfender E (2007) Thermodynamic and transport properties of two-temperature oxygen plasmas. Plasma Chem Plasma Process 27:267–291
16. Huang PC, Heberlein J, Pfender E (1995) A two-fluid model of turbulence for a thermal plasma jet. J Plasma Chem Plasma Process 15(1):25–46
17. Johnson DC, Pfender E (1983) The effects of low-ionization-potential contaminants on thermal plasmas. Plasma Chem Plasma Process 3(2):259–273
18. Lee YC, Pfender E (1985) Particle dynamics and particle heat and mass transfer in thermal plasmas. Part I. The motion of a single particle without thermal effects. Plasma Chem Plasma Process 5(3):212–237
19. Lee YC, Chyou YP, Pfender E (1985) Particle dynamics and particle heat and mass transfer in thermal plasmas. Part II. Particle heat and mass transfer in thermal plasmas. Plasma Chem Plasma Process 5(4):391–414
20. Lee YC, Pfender E (1987) Particle dynamics and particle heat and mass transfer in thermal plasmas. Part III. Thermal plasma jet reactors and multi-particle injection. Plasma Chem Plasma Process 7(1):1–27
21. Menart J, Heberlein J, Pfender E (1996) Theoretical radiative emission results for argon/copper thermal plasmas. Plasma Chem Plasma Process Press 16(1):246S–265S

22. Mostaghimi-Tehrani J, Pfender E (1984) Effects of metallic vapor on the properties of an argon arc plasma. Plasma Chem Plasma Process 4(2):129–139
23. Paik S, Pfender E (1990) Argon plasma transport properties at reduced pressures. Plasma Chem Plasma Process 10(2):291–304
24. Park J, Heberlein J, Pfender E, Candler G, Chang CH (2008) Two-dimensional numerical modeling of direct-current electric arcs in non-equilibrium. Plasma Chem Plasma Process 28:213–231
25. Pfender E, Fincke J, Spores R (1991) Entrainment of cold gas into thermal plasma jets. J Plasma Chem Plasma Process 11(4):529–543
26. Pfender E (1989) Particle behavior in thermal plasmas. Plasma Chem Plasma Process 9(1):167S–194S
27. Pfender E (1999) Thermal plasma technology: where do we stand and where are we going? Plasma Chem Plasma Process 19(1):1–31
28. Pfender E (1997) Editorial advances in modeling of the thermal spray process. J Therm Spray Technol 6(2):126–128
29. Pfender E, Lee YC (1985) Particle dynamics and particle heat and mass transfer in thermal plasmas. Part I. The motion of a single particle without thermal effects. Plasma Chem Plasma Process 5(3):211
30. Russ S, Pfender E, Strykowski PJ (1994) Unsteadiness and mixing in thermal plasma jets'. J Plasma Chem Plasma Process 14(4):425–436
31. Russ S, Strykowski PJ, Pfender E (1994) Mixing in plasma and low density jets. Exp Fluids 16:297–307
32. Trelles JP, Pfender E, Heberlein J (2006) Multiscale finite element modeling of arc dynamics in a DC plasma torch. Plasma Chem Plasma Process 26:557–575
33. Wilhelmi H, Lyhs W, Pfender E (1984) Calculation of thermodynamic and transport properties of a typical arc furnace plasma. Plasma Chem Plasma Process 4(4):315–323
34. Young RM, Pfender E (1985) Generation and behavior of fine particles in thermal plasmas—a review. Plasma Chem Plasma Process 5(1):1–37
35. Young RM, Pfender E (1985) Generation and behavior of fine particles in thermal plasmas—a review. Plasma Chem Plasma Process 5(1):1–32