JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 38, No. 2, March–April 2001

Scaling Nonequilibrium-Reacting Flows: The Legacy of Gerhard Damköhler

George R. Inger*
Iowa State University, Ames, Iowa 50011

Damköhler's personal background is first outlined, followed by an examination of his early pioneering work in the 1930s on reacting flows, which led to the basic nondimensional similitude parameters that now bear his name. We then survey the role that these parameters have played in dealing with finite reaction-rate effects in acoustics, combustion, and the aerothermodynamics of hypervelocity flight vehicles and their propulsion systems. Emphasis is placed on the aerospace sciences and the value of the Damköhler number not only in understanding and correlating experimental data, but also in conducting efficient numerical studies and analyses of reacting-gas flowfields.

Nomenclature

A	=	cross-sectional area
C_1	=	nondimensional recombination parameter[24]
D	=	body diameter
$\mathcal{D}$	=	diffusion coefficient
$Da_{\mathrm{I,II,III}}$	=	Damköhler numbers defined in Eqs. (1–3)
H	=	total enthalpy
k, k'	=	characteristic gas-phase reaction-rate constants
Le	=	Lewis number
ℓ	=	characteristic dimension
M	=	Mach number
N_u	=	Nusselt number
P_R	=	Prandtl number
q	=	heat-transfer rate
q_D	=	diffusion heat transfer
R_B	=	body nose radius
Re_ℓ	=	characteristic Reynolds number based on ℓ, $\rho \dot{U} \ell / \mu$
S	=	flame speed
T	=	static temperature
T_s	=	stagnation temperature
U	=	characteristic flow velocity
Γ_c	=	catalytic Damköhler number for stagnation flow[28]
Γ_G	=	gas-phase recombination Damköhler number for stagnation flow[28]
$\tilde{\Gamma}_i$	=	interactive catalytic Damköhler number[33]
ε	=	turbulent eddy viscosity
η	=	surface catalytic efficiency
μ	=	laminar viscosity coefficient
ρ	=	density

Subscripts

EQ	=	chemical equilibrium
F	=	chemically frozen flow
GAS	=	gas phase
L	=	laminar
O	=	undisturbed upstream value
SURFACE	=	body surface
T	=	turbulent
THROAT	=	nozzle throat
VIB	=	nonequilibrium molecular vibration
W	=	wall surface conditions
∞	=	freestream conditions

Prolog

THE middle 1930s found the chemical engineering and combustion disciplines as still largely empirical technologies. What few fundamentals to be found consisted of the elementary thermal model of flame propogation given by Mallard and Le Chatlier[1] in 1883, the studies of detonation by Chapman and Jouget[2] in 1900, some work of Burke and Schumann[3] on diffusion flames in 1928, and a combustion textbook by Jost[4] that was about to appear. Little basic analytical work had been done on reacting open flow systems and combustion that could serve as a foundation for industrial process design or improvement.

Coming upon this scene, Damköhler set himself a systematic program of research to remedy the situation and in so doing had an enormous impact on the engineering sciences of both chemical engineering and later aerospace engineering. Yet his career has always seemed somehow shrouded in relative obscurity. This obscurity is partially understandable because of the fact that, aside from some postwar NACA translations, all of his work was published in German language chemical engineering journals with most coming out under wartime conditions after 1939. Nevertheless, there remains an air of vagueness about a man so technically influential.

This paper presents an overview of Damköhler's life and work that seeks to place in perspective his many contributions not only to the fundamentals of chemical engineering but also as they carried over into the modern post-WWII field of aerospace engineering. As such, this is not intended to be a state-of-the-art review of any aspect of either field but rather an overall assessment of Damköhler's contributions and the conditions under which they were made. The examples selected are not exhaustive (for example, we do not take up topics involving separated flows and wakes) and necessarily reflect some of the author's interests, but are believed to serve the aforementioned overall goal.

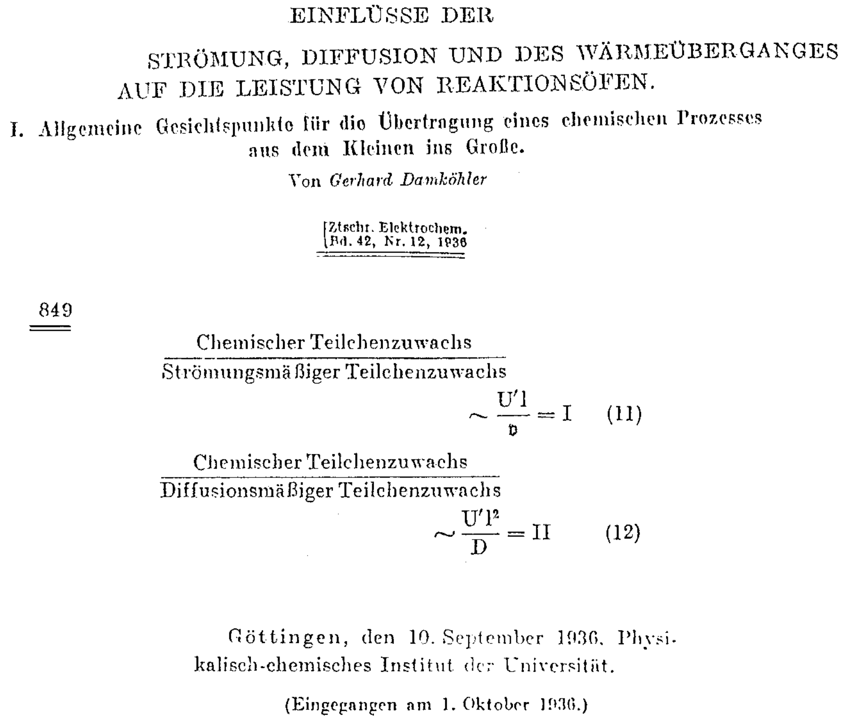
Damköhler's Early Work

We learn from Wicke[5] that Gerhard Damköhler was born on 16 March 1908 in Klingenmünster in West Central Germany, the son of a physician. Following the usual primary and gymnasium education, he enrolled in the summer of 1926 at the University of Munich to study chemistry with A. Sommerfeld, graduating five years later summa cum laude with a doctor of philosophy for a dissertion entitled "Individuality of the Osmotic Behaviour of Alkalihalogenides." He remained at the university for three more years as a grant-supported research fellow, during which time he began to display a marked ability for developing and applying analytical methods to practical problems in chemical engineering. This work attracted the notice of Arnold Eucken, the director of Göttingen University's Institute of Physical Chemistry, who offered Damköhler a position as an assistant that he took up in December 1934.

Under Eucken's mentorship, Damköhler's theoretical work prospered even more, culminating in a concerted effort to provide a

Received 3 March 2000; revision received 8 October 2000; accepted for publication 12 October 2000.

*Professor, Aerospace Engineering and Engineering Mechanics Department. Associate Fellow AIAA.



EINFLÜSSE DER STRÖMUNG, DIFFUSION UND DES WÄRMEÜBERGANGES AUF DIE LEISTUNG VON REAKTIONSÖFEN.

I. Allgemeine Gesichtspunkte für die Übertragung eines chemischen Prozesses aus dem Kleinen ins Große.

Von *Gerhard Damköhler*

[Ztschr. Elektrochem. Bd. 42, Nr. 12, 1936

849

$$\frac{\text{Chemischer Teilchenzuwachs}}{\text{Strömungsmäßiger Teilchenzuwachs}} \sim \frac{U'l}{\mathfrak{v}} = \text{I} \quad (11)$$

$$\frac{\text{Chemischer Teilchenzuwachs}}{\text{Diffusionsmäßiger Teilchenzuwachs}} \sim \frac{U'l^2}{D} = \text{II} \quad (12)$$

Göttingen, den 10. September 1936. Physikalisch-chemisches Institut der Universität.

(Eingegangen am 1. Oktober 1936.)

Fig. 1 Damköhler's classical paper on the similitude of finite chemical rate effects in open flow systems.

coherent basic theory of the combined role of finite rate chemical reactions and diffusion in open flow systems. To improve his understanding of hydrodynamics, Damköhler attended Prandtl's lectures. Following a survey paper, a number of contributions followed in quick succession dealing with specific applications to simple chemical reactor flows[5] capped off by his seminal paper[6] of October 1936 that examines the application of similarity theory to flow systems with finite rate chemistry and diffusion present (Fig 1). This study led to the identification of the two nondimensional parameters that now bear his name:

$$\frac{\text{Chemical Flux}}{\text{Convectional Flux}} = \frac{\text{Flow Time}}{\text{Reaction Time}} = \frac{k_{\text{GAS}} \cdot \ell}{U} = Da_{\text{I}} \quad (1)$$

$$\frac{\text{Chemical Flux}}{\text{Diffusional Flux}} = \frac{\text{Diffusion Time}}{\text{Reaction Time}} = \frac{k_{\text{SOLID}} \cdot \ell^2}{\mathcal{D}} = Da_{\text{II}} \quad (2)$$

Following this groundbreaking paper (which has since been much cited), Damköhler pursued applications to various types of generic reactor flow involving both gas-phase and catalytic surface reactions.[5]

On the basis of the aforementioned research work, Damköhler received his habilitation in the spring of 1937 accompanied by the probationary lecture "On the Physico-Chemical Basis of Material Separation Processes." Figure 2 shows a May 1937 picture of Eucken's research group taken in front of the Institute of Physical Chemistry (the building is still there); it includes a smiling white-coated Damköhler to the right behind the young boy in the first row. By October of 1937, however, he had departed for Braunschweig, where he became an associate of Ernst Schmidt in the Aeronautical Research Establishment's Motors Research Institute. Damköhler promptly completed a systematic summary of his various investigations for the Handbuch der Chemie in the highly regarded and influential article, "The Influence of Diffusion, Flow and Heat Transport on Yield in Chemical Reactors."[7] Further practical studies carried out in the next three years resulted in yet another survey paper[8] in which particular attention was paid to exothermic homogeneous reaction in flames and internal combustion engines.

It was thus that Damköhler moved into another area of innovative and influential research, namely the study of turbulent flames.[9] His was the first systematic quantitative experimental and theoretical examination of how premixed flames propagated and wrinkled under

Fig. 2 May 1937 photo of the members of the Physikalisch-Chemisches Institute—Göttingen; Damköhler is in the white coat, second row, fourth from the left, two places down from the Director, Arnold Eucken.

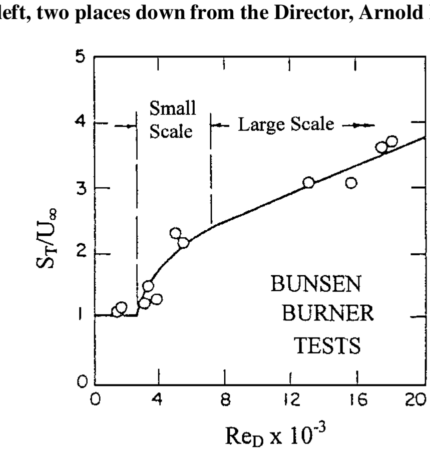


Fig. 3 Damköhler's groundbreaking 1940 study of turbulent flame speed vs Reynolds number (later translated as NACA TM-1112, 1947).

the influence of turbulent fluctuations (Fig. 3). To characterize the effects of turbulence, he introduced yet another "turbulent Damköhler Number" involving the eddy viscosity to laminar viscosity ratio ε/μ, defined by

$$Da_{\mathrm{III}} = (\varepsilon/\mu)^{\frac{1}{2}} \cdot Da_{\mathrm{I}} \tag{3}$$

which has since been widely employed in modern follow-on studies. Seeking an improved basis for the use of sound dispersion measurements as a flame diagnostic, Damköhler also undertook a very elaborate study of sound propagation in chemically reacting flows, which was published in wartime Germany and only translated in the United States nearly a decade later[10] (Fig. 4).

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

TECHNICAL MEMORANDUM 1268
TECHNICAL MEMORANDUM 1269

ISENTROPIC PHASE CHANGES IN DISSOCIATING GASES AND THE
METHOD OF SOUND DISPERSION FOR THE INVESTIGATION OF
HOMOGENEOUS GAS REACTIONS WITH VERY HIGH SPEED

By Gerhard Damköhler

Translation of "Isentropische Zustandsänderungen in Dissoziierenden Gasen und die Methode der Schalldispersion zur Untersuchung sehr Schneller Homogener Gasreaktionen."
Zeitschrift für Elektrochemie, Bd. 48, Nr. 2, 1942

NACA

Washington
September 1950

Fig. 4 Delayed posthumous translation of Damköhler's research on acoustics in reacting gases.

Influence of Damköhler's Work on the Postwar Aerospace Sciences

The post-WWII emergence of the then new field of aerothermochemistry brought attention to Damköhler's earlier (and perhaps obscure) work by researchers working in aerospace propulsion, hypervelocity vehicle heating, and high-speed flight simulation. This awareness appears to have been fostered by Theodore von Kármán in his famous Sorbonne Lectures[11] of 1952–53.

Combustion Aerothermodynamics

Von Kármán's influence quickly bore fruit through his collaborator S.S. Penner, who in 1955 comprehensively summarized Damköhler's ideas on the similitude of reacting flows and their implications for the scaling of chemical reactors and liquid rocket engineers.[12] S. Way and others followed with analogous treatment of aircraft gas turbine combustors.[13] In addition to such overall scaling studies, however, Damköhler's work had delved into the detailed aerothermodynamics of the flow itself, and this too was now being rediscovered. A good example is his early 1940s research on turbulent flames just mentioned: after its 1947 NACA translation[9] made it more widely available, it became the very influential foundation for expanded research that followed in the 1960s onward (Fig. 5) (Ref. 14). [According to Ref. 15, "the theoretical understanding of premixed turbulent flames by subsequent work to 1965 was not much greater than that originally developed by Damköhler" (Ref. 15, p. 373).] The concept of using the turbulent Damköhler number as the appropriate similitude parameter was also later used in studies of gaseous fuel/air mixture "flashback" in ducts, the blowoff (extinction) of flames anchored on flame holders in high-speed streams, and the burning of fuel droplets.[16] The physical implications of the Damköhler number as a characteristic flow/chemical time ratio have also lead to its use as the basis for asymptotic perturbation method analyses of flames and reacting flows ("Damköhler Asymptotics")[17]:

$$Da = \frac{\text{FlowTime}}{\text{ChemTime}} = \frac{\ell/U}{1/k} = \frac{k\ell}{U} \tag{4}$$

where $Da \rightarrow 0$ for chemically frozen flow, whereas $Da \rightarrow \infty$ for local chemical-equilibrium flow. Finally, we note that Damköhler scaling ideas continue to be useful in the many contemporary studies of combustor performance in scramjet engines.[18]

Real-Gas Dynamics of Inviscid Flowfields

The advent of serious interest in hypervelocity flight at very high altitude in the late 1950s naturally focused attention on

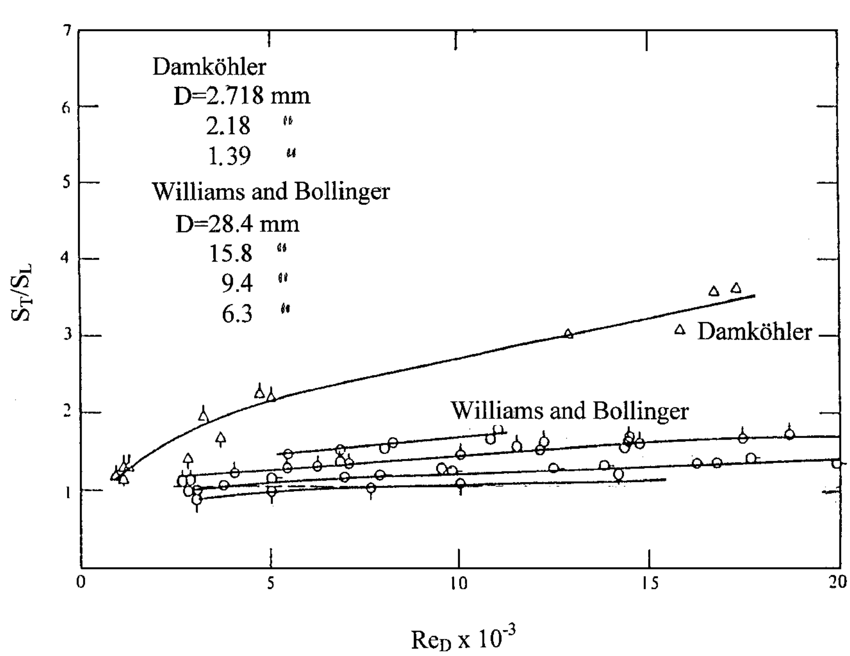


Fig. 5 Damköhler's work compared to later modern studies on turbulent flames (from Williams and Bollinger[14]).

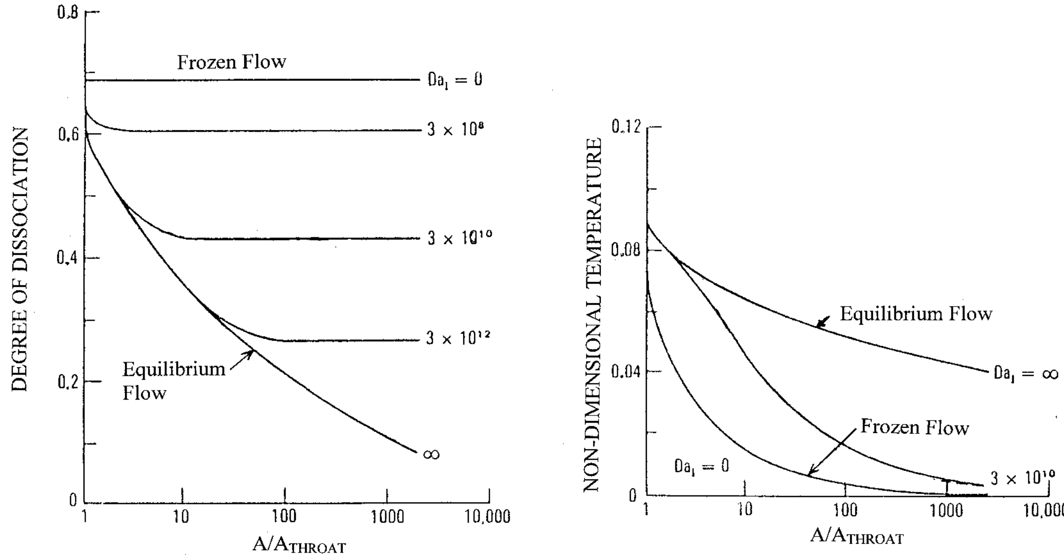


Fig. 6 Results of a theoretical study of nonequilibrium dissociated flow in a hyperbolic nozzle, with a nozzle-based Da_I as the correlating parameter (from Bray[19]).

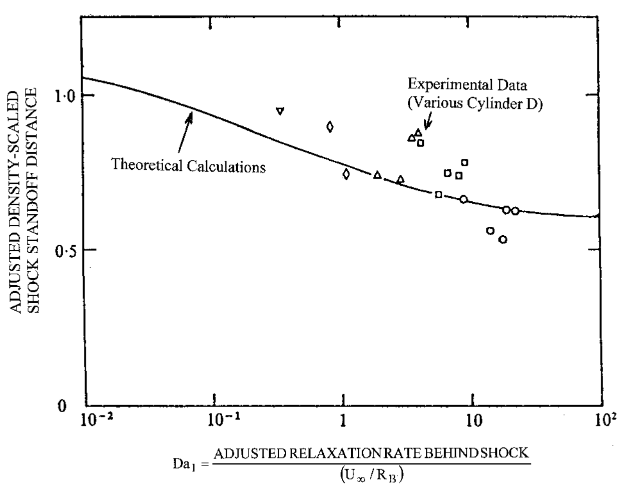


Fig. 7 Hornung's study of nonequilibrium circular cylinder flow using an appropriate blunt-body Da_I as the correlating parameter.[20]

understanding high-temperature gas flows containing significant amounts of excited molecular vibration and dissociation. Owing to the need to reduce aerodynamic heating, blunt-nosed aerodynamic configurations and their inviscid flowfields that would contain such real-gas effects became an especially important research topic.

When it was appreciated that nonequilibrium effects could be very significant for high-flight-speed/high-altitude operating conditions, the value of Damköhler's similitude concepts arose again. Thus in a well-known theoretical study of chemical freezing within a hyperbolic nozzle flow of ideal dissociating gas, Bray[19] found that his results could be revealingly correlated in terms of an appropriate "nozzle Damköhler Number" (Fig. 6). In a similar vein Hornung[20] employed another type of Damköhler number based on the postshock dissociation rate to correlate experimental data from an interferometric study of a simple blunt-nose region flow for a circular cylinder plus a large number of theoretical calculations (Fig. 7). Comparable work has been done on the purely vibrational aspects, where a Landau–Teller type of model is employed for the relaxation of the nonequilibrium molecular vibrational energy in conjunction with an appropriate Damköhler number $Da_{\text{vib}} = k_{\text{vib}}\ell/U$ such that $Da_{\text{vib}} \gg 1$ implies local equilibrium between translational and vibrational temperatures.[21]

An important byproduct of Damköhler's similitude concepts applied to nonequilibrium-dissociated blunt-body flows emerged in 1962: the binary scaling concept put forward and computationally validated by Gibson.[22] According to this concept, the scaled prop-

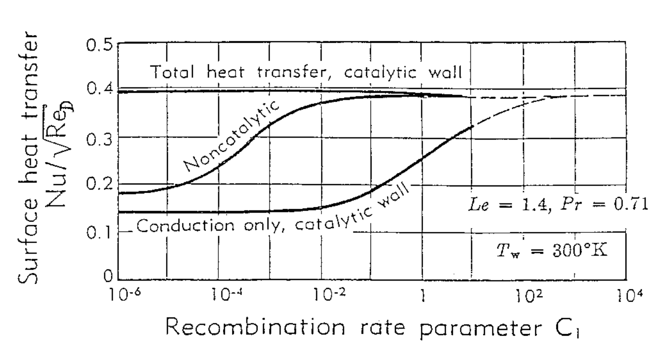


Fig. 8 Fay and Riddell's well-known result for the effect of finite gas-phase recombination rate on cold wall heating to either a fully catalytic or completely noncatalytic surface.[25]

erties of any nonequilibrium-dissociated flow of a given gas with negligible recombination at a fixed flight velocity will be the same for all different combinations of body size (nose radius) and altitude (ambient density) if the product $\rho_\infty R_B$ is the same. Such binary scaling can be understood by applying the Damköhler number definition of Eq. (1) to the case of a dissociation-dominated nonequilibrium flow ($k_{\text{GAS}} \sim \rho k_R' \sim \rho_\infty k_R'$) in the stagnation of a blunt body where $U \sim (U_\infty/R_B)\ell$:

$$Da_I = \rho_\infty R_B k_R' / U_\infty \tag{5}$$

implying that similar flows (same Da_I) at a fixed U_∞ must have the same value of $\rho_\infty R_B$. The value of this idea in experimental simulation work is now widely appreciated and in fact has been extended to slender hypersonic bodies[23] as well as certain types of nonequilibrium boundary-layer flows.[24]

Dissociated Boundary-Layer Flows

The concern with aerodynamic heating on hypervelocity vehicles naturally led to research on the effects of dissociation on heat transfer under conditions of gas-phase nonequilibrium chemistry and finite surface catalycity pertaining to high-velocity/high-altitude flight conditions. Regarding blunt bodies, this concern led to the famous Fay and Riddell[25] stagnation region similarity solution for cold walls and arbitrary gas-phase recombination rates (Fig. 8), closely followed by Goulard's[26] classic paper on the same problem in the chemically frozen limit that described the effects of an arbitrary surface catalycity on conductive and diffusional heating (Fig. 9). Neither of these authors identified their respective finite reaction-rate parameters as Damköhler numbers (Da_I and Da_{II}) appropriate to stagnation type of flow. Rosner,[27] Chung,[28] and Inger,[29]

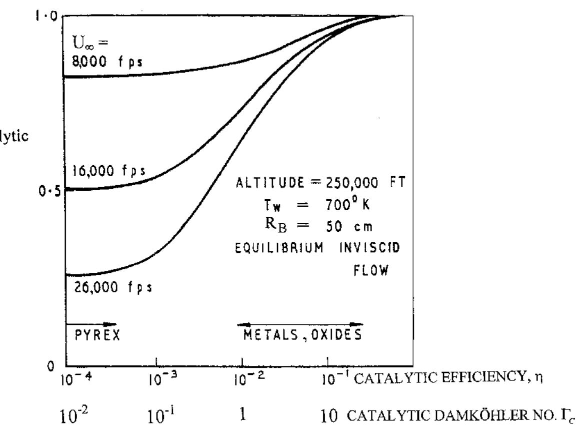


Fig. 9 Effect of wall catalysis on stagnation heat transfer in frozen dissociated flow (adapted from Ref. 26).

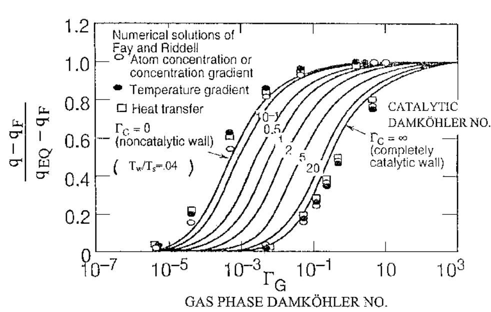


Fig. 10 Stagnation heat-transfer theory for the combined Fay and Riddell/Goulard problem using Damköhler similarity ideas with arbitrary gas nonequilibrium and surface catalycity.[29]

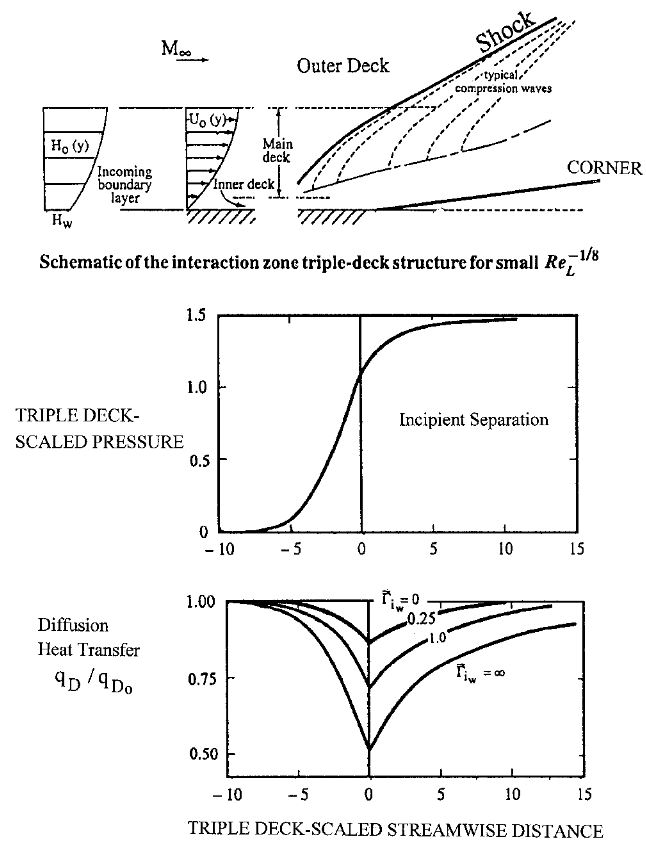


Fig. 11 "Interactive" Damköhler number correlation of local heat transfer in a shock/boundary-layer interaction.[34]

however, made full use of the resulting similitude implications for both blunt-nosed and slender bodies. In addition to providing a clear physical interpretation of the extremes of nonequilibrium behavior within boundary layers (frozen vs equilibrium gas-phase/full catalytic vs noncatalytic surfaces), such work resulted in a combined treatment of the Fay and Riddell/Goulard problems that yielded an accurate closed-form result for heating for arbitrary values of both the gas-phase and heterogeneous Damköhler numbers[29] (Fig. 10). Moreover, this work established a universal master nonequilibrium scaling parameter for highly cooled recombination-dominated stagnation boundary layers that has since proven a valuable guide in interpreting both experimental data[30] and computational fluid dynamics calculations on nonequilibrium heating.[31] The information conveyed by Figs. 8–10 is still of great interest to contemporary researchers and designers of reentry vehicle physics in showing how the effect of surface catalycity on heat transfer is altered by the gas-phase recombination parameter.

Further contributions that exploited Damköhler Asymptotics clarified understanding of the limiting behavior in both nearly equilibrium[32] and highly nonequilibrium[33] (nearly frozen) regimes for slender wedge/cone body shapes of interest to the reentry vehicle/interceptor missile community. As one would expect, the Damköhler number has also played a role in studies of surface ablation/combustion phenomena.[28] More recently, application has even arisen in conjunction with the study of shock/boundary-layer interaction in reacting dissociated flows[34] (Fig. 11), leading to the identification of a new "interactive" type of Damköhler number.

Epilog

Following the 1943 publication of two papers on absorption and catalysis,[5] no further papers by Damköhler appear in the German literature. Further inquiry has revealed why: at the age of 36, he tragically took his own life on 30 March 1944. Part of the reason appears rooted in a conflict that developed between him and the wartime national socialist government. The scientific reputation he had built up by 1940 had attracted an offer of a chair in Chemical Engineering at Darmstadt University, but this position fell through when he demanded that his research be free from political influence. Clearly, Damköhler's combustion -related studies at Braunschweigs' Motors Research Institute was of direct relevance to the Luftwaffe's jet engine development program, and pressure was undoubtedly brought to bear for him to become more involved—at which his intellectually independent spirit must have rebelled. Another contributing factor lies in Damköhler's personality and private life: he has been consistently described as a highly intelligent man who, however, worked himself "25 hours a day" with little regard for the childless homelife he shared with his wife of seven years (Ref. 5; Ernst Schmidt, "Funeral Remarks 1944," as quoted by Wicke in Ref. 5; H. Wagner, personal interview with the author, Göttingen, Germany, April 1999). One can easily imagine how such a work style, combined with a socially imbalanced personal life and the aforementioned political pressures, could have led to a breakdown in such a brilliant but driven man.

How should we then finally sum up this highly influential yet tragic figure? First, by emphasizing the powerful similitude principles that bear his name: each of the three ratios defined by Eqs. (1–3) must be the same for aerothermochemical similarity of flows with finite rate chemistry. When appropriately defined for the problem at hand, this legacy continues to guide contemporary theoretical and experimental studies of reacting gas dynamics. Second, by noting what is perhaps the best epitaph an engineer could have, in the form of the following assessment by Professor H. Wagner (personal interview): "twenty-five percent of all the important processes and methods currently employed by the German Chemical Industry are directly attributed to the principles laid down by Damköhler." For this, he is memorialized to this day by the annual Deutsche Vereinigung für Chemie — und Verfahrenstechnik (DVCV) Gerhard Damköhler Medaille. The author hopes that the present paper has succeeded in showing that his influence significantly reached out (and continues to do so) into the modern aerospace sciences as well.

Acknowledgments

I wish to thank Klaus Hanneman of the DLR,German Aerospace Research Center, and H. Wagner of the Institute for Physical

Chemistry for their enthusiastic and valuable help while I researched Damköhler's life and work during my visit to Göttingen in April 1999.

References

[1]Mallard, E., and LeChatelier, H. L., "Thermal Model for Flame Propagation," *Ann. Mines*, Vol. 4, No. 18, 1983, p. 379.

[2]Chapman, D., and Jouget, E., "Theory of Detonation Wave Propagation," *Philosophical Magazine*, Vol. 27, No. 1, 1899, pp. 90–105.

[3]Burke, S. P., and Schumann, T., "Analysis of Diffusion Flames," *Industrial and Engineering Chemistry*, Vol. 20, No. 10, 1928, pp. 998–1004.

[4]Jost, W., *Explosions—und Verbremmungsvozgänger in Gasen*, Springer-Verlag, Berlin, 1939.

[5]Wicke, E., "Gerhard Damköhler—Founder of Chemical Reaction Engineering," *International Chemical Engineering*, Vol. 25, No. 4, 1985, pp. 770–773.

[6]Damköhler, G., "Einflüsse der Strömung, Diffusion und des Wärmeüberganges auf die Leitstung von Reationsöfen," *Zeitschrift für Electroche*, Vol. 42, No. 12, 1936, pp. 846–862.

[7]Damköhler, G., "The Influence of Diffusion, Flow and Heat Transport on Yield in Chemical Reactors," *Der Chemie-Ingenieur*, Vol. III, edited by M. Jakob, and A. Euken, Pt. 1, Academy Verlagages Liepzig, 1937, pp. 539–568.

[8]Damköhler, G., "Exothermic Homogeneous Reactions in Flames and Internal Combustion Engines," *Der Chemie-Ingenieur*, Vol. III, edited by M. Jakob, and A. Euken, Pt. 5, Academy Verlagages Liepzig, 1940, pp. 321–339.

[9]Damköhler, G., "Der Einfluss der Turbulenz auf die Flammengeschwindigkeit in Gasgemisch," *Zeitschrift Electrochemie Angewandte. Physik. Chemie*, NACA TM. 1112, 1947, Vol. 46, No. 3, 1940, pp. 601–626; (English. Translation).

[10]Damköhler, G., "Isentropic Phase Changes in Dissociating Gases and the Method of Sound Dispersion for the Investigation of Homogeneous Gas Reactions with Very High Speed," NACA TM 1268 and 1269, 1950 (translation of article in *Zeitschrift für Elektrochemie*), Vol. 48, No. 2, 1942, pp. 116-131.

[11]von Kármán, Th., *Sorbonne Lectures*, 1952–53, Paris; see "Fundamental Equations in Aerothermochemistry," *Collected Works of Th. Von Kármán, 1952–1963*, Butterworths, London, 1975, pp. 131–150.

[12]Penner, S. S., "Similarity Analysis for Chemical Reactors and the Scaling of Liquid Fuel Rockets," *Combustion Researches and Reviews*, Butterworths, London, 1955, pp. 140–162.

[13]Way, S., "Combustion in the Turbojet Engine," *Selected Combustion Problems II*, Butterworths, London, 1956, pp. 296–327.

[14]Williams, D. T., and Bollinger, L. M., "The Effect of Turbulence on Flame Speeds of Bunsen-Flames," *Third Symposium on Combustion and Flame and Explosion Phenomena*, Williams and Wilkins, Baltimore, 1949, pp. 176–185.

[15]Williams, F., *Combustion Theory*, 2nd ed., Benjamin/Cummings, Menlo Park, CA, 1985, p. 373.

[16]Rosner, D., *Transport Processes in Chemically Reacting Flow Systems*, Butterworths, London, 1986, pp. 429–431.

[17]Williams, F., *Combustion Theory*, 2nd ed., Benjamin/Cummings, Menlo Park, CA, 1985, pp. 72, 176.

[18]Mitoni, T., Chinzeiand, N., and Kanda, T., "Reaction and Mixing—Controlled Combustion in Scramjet Engines," AIAA Paper 99-4871, Nov. 1999.

[19]Bray, K. N. C., "Atomic Recombination in a Hypersonic Wind-Tunnel Nozzle," *Journal of Fluid Mechanics*, Vol. 6, No. 1, 1959, pp. 1–32.

[20]Hornung, H. G., "Non-Equilibrium Dissociating Nitrogen Flow over Spheres and Circular Cylinders," *Journal of Fluid Mechanics*, Vol. 53, No. 5, 1972, pp. 149–176.

[21]Gnoffo, P. A., "Planetary Entry Gas Dynamics," *Annual Review of Fluid Mechanics*, Vol. 31, 1999, pp. 459–499.

[22]Gibson, W., "Dissociation Scaling for Nonequilibrium Blunt Nose Flows," *ARS Journal*, Vol. 32, No. 2, 1962, pp. 285–287.

[23]Inger, G. R., "Similitude of Hypersonic Flows over Slender Bodies in Nonequilibrium-Dissociated Gases," *AIAA Journal*, Vol. 1, No. 1, 1963, pp. 46–53.

[24]Lee, R. M., and Levinsky, E. S., "Binary Scaling of the Nonequilibrium Boundary Layer over Slender Bodies," *Proceedings of the 1964 Heat Transfer and Fluid Mechanics Institute*, Stanford Univ. Press, Stanford, CA, 1964, pp. 115–129.

[25]Fay, J. A., and Riddell, F. R., "Theory of Stagnation Point Heat Transfer in Dissociated Air," *Journal of Aerospace Science*, Vol. 25, No. 2, 1958, pp. 73–85.

[26]Goulard, R., "On Catalytic Recombination Rates in Hypersonic Stagnation Heat Transfer," *Jet Propulsion*, Vol. 28, No. 5, 1958, pp. 737–745.

[27]Rosner, D. E., "Similitude Treatment of Hypersonic Stagnation Heat Transfer," *ARS Journal*, Vol. 29, No. 3, 1959, pp. 215, 216.

[28]Chung, P., "Chemically Reacting Nonequilibrium Boundary Layers," *Advances in Heat Transfer*, Academic Press, New York, 1966, pp. 109–271.

[29]Inger, G. R., "Non-Equilibrium Stagnation Point Boundary Layers with Arbitrary Surface Catalycity," *AIAA Journal*, Vol. 1, No. 8, 1963, pp. 1776–1783.

[30]Mudford, N. R., Gai, S. L., and Mallison, S. F., "Boundary Layer Recombination Pathways in Bluff Body Flows in a Shock Tunnel," *Proceedings of the 21st International Symposium on Shock Waves*, edited by F. Houwing, Australian National Univ., Canberra, 1997, p. 155.

[31]Inger, G. R., and Gnoffo, P. G., "Analytic Corrections to Computational Heating Predictions Accounting for Changes in Surface Catalysis," *Journal of Spacecraft and Rockets* Vol. 35, No. 4, 1998, pp. 417–423.

[32]Inger, G. R., "Nearly-Equilibrium Dissociated Boundary Layer Flows by the Method of Matched Asymptotic Expansion," *Journal of Fluid Mechanics*, Vol. 26, Pt. 4, Dec. 1966, pp. 793–806.

[33]Inger, G. R., "Highly Nonequilibrium Boundary Layer Flows of a Multicomponent Dissociated Gas Mixture," *International Journal of Heat and Mass Transfer*, Vol. 7, No. 8, 1964, pp. 1151–1174.

[34]Inger, G. R., "Shock-Viscous Interaction Heating in Nonequilibrium-Dissociated Flows Along Arbitrarily-Catalytic Surfaces," *Journal of Thermophysics and Heat Transfer*, Vol. 13, No. 3, 1999, pp. 379–382.

T. C. Lin
Associate Editor