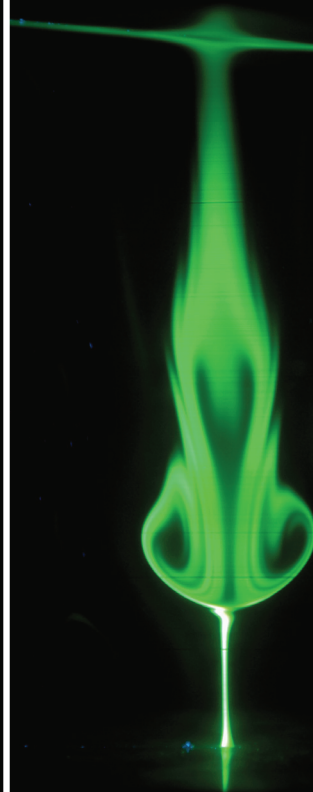
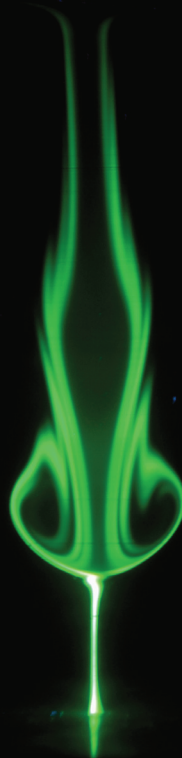


CAMBRIDGE
UNIVERSITY PRESS

25 September 2013

Journal of Fluid Mechanics

VOLUME 731



SUBSCRIPTIONS

The *Journal of Fluid Mechanics* (ISSN 0022-1120) is published *semimonthly* in 24 volumes each year by Cambridge University Press, The Edinburgh Building, Shaftesbury Road, Cambridge CB2 8RU, UK/Cambridge University Press, 32 Avenue of the Americas, New York, NY 10013-2473, USA. The subscription price (excluding VAT but including postage) for volumes 714–737, 2013, is £3037 or \$5605 (online and print) and £2657 or \$4654 (online only) for institutions; £867 or \$1606 (online and print) and £824 or \$1432 (online only) for individuals. The print-only price available to institutional subscribers is £2902 (US \$5108 in USA, Canada and Mexico). Single volumes cost £131 (US \$233 in the USA, Canada and Mexico) plus postage. Orders, which must be accompanied by payment, should be sent to any bookseller or subscription agent, or direct to the publisher: Cambridge University Press, The Edinburgh Building, Shaftesbury Road, Cambridge CB2 8RU. Subscriptions in the USA, Canada and Mexico should be sent to Cambridge University Press, Journals Fulfillment Department, 100 Brook Hill Drive, West Nyack, NY 10994-2133. EU subscribers (outside the UK) who are not registered for VAT should add VAT at their country's rate. VAT registered subscribers should provide their VAT registration number. Japanese prices for institutions are available from Kinokuniya Company Ltd, PO Box 55, Chitose, Tokyo 156, Japan. Prices include delivery by air. Copies of the *Journal* for subscribers in the USA, Canada and Mexico are sent by air to New York. Periodicals postage is paid at New York, NY, and at additional mailing offices. POSTMASTER: send address changes in USA, Canada and Mexico to *Journal of Fluid Mechanics*, Cambridge University Press, 100 Brook Hill Drive, West Nyack, NY 10994-2133. Claims for missing issues can only be considered if made immediately upon receipt of the subsequent issue. Copies of back numbers are available from Cambridge University Press.

COPYING

The *Journal* is registered with the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923. Organizations in the USA which are also registered with CCC may therefore copy material (beyond the limits permitted by sections 107 and 108 of US copyright law) subject to payment to CCC of the per-copy fee of \$16.00. This consent does not extend to multiple copying for promotional or commercial purposes. Code 0022-1120/2013/\$16.00.

ISI Tear Sheet Service, 3501 Market Street, Philadelphia, PA 19104, USA is authorized to supply single copies of separate articles for private use only.

Organizations authorized by the Copyright Licensing Agency may also copy material subject to the usual conditions.

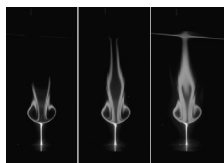
For all other use of material from the *Journal* permission should be sought from Cambridge or the American Branch of Cambridge University Press.

Information on *Journal of Fluid Mechanics* is available on journals.cambridge.org/FLM. For further information on other Press titles access cambridge.org/.

Readers should note that where reference is made to a Web site for additional material relating to an article published in *Journal of Fluid Mechanics* this material has not been refereed and the Editors and Cambridge University Press have no responsibility for its content.

This journal issue has been printed on FSC-certified paper and cover board. FSC is an independent, non-governmental, not-for-profit organization established to promote the responsible management of the World's forests. Please see www.fsc.org for information.

Printed in the UK by Bell & Bain Ltd.



The picture on the cover is based on figure 2(c) of 'Mixing in a vortex breakdown flow', by P. Meunier & K. Hourigan. The cover montage shows the temporal evolution of the dye.

The JOURNAL OF FLUID MECHANICS exists for the publication of theoretical, computational and experimental investigations of all aspects of the mechanics of fluids.

EDITOR

Prof. M. G. Worster, Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Centre for Mathematical Sciences, Wilberforce Road, Cambridge CB3 0WA, UK. mgw.jfm@damtp.cam.ac.uk

DEPUTY EDITORS

Prof. P. F. Linden, Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Centre for Mathematical Sciences, Wilberforce Road, Cambridge CB3 0WA, UK. p.f.linden@damtp.cam.ac.uk

Prof. C. Meneveau, Department of Mechanical Engineering and Center for Environmental and Applied Fluid Mechanics, Johns Hopkins University, 3400 N. Charles Street, Baltimore, MD 21218, USA.
meneveau@jhu.edu

BOOK REVIEW AND FOCUS ON FLUIDS EDITOR

Dr C. P. Caulfield, DAMTP, University of Cambridge, Centre for Mathematical Sciences, Wilberforce Road, Cambridge CB3 0WA, UK. c.p.caulfield@damtp.cam.ac.uk

ASSOCIATE EDITORS

Prof. N. Balmforth, Department of Mathematics, University of British Columbia, Vancouver, BC, Canada V6T 1Z2. njb@math.ubc.ca

Prof. D. Barthès-Biesel, Génie Biologique, Université de Technologie de Compiègne, BP 20529, Compiègne 60205, France. dbb@utc.fr

Prof. O. Bühler, Courant Institute of Mathematical Sciences, New York University, 251 Mercer Street, New York, NY 10012-1185, USA.
obuhler@cims.nyu.edu

Prof. J.-M. Chomaz, LadHyX–CNRS–Ecole Polytechnique, 91128 Palaiseau CEDEX, France.
jfm.chomaz@ladhyx.polytechnique.fr

Prof. P. A. Davidson, Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, UK. pad3@eng.cam.ac.uk

Prof. J. Duncan, Department of Mechanical Engineering, University of Maryland, College Park, MD 20742, USA. duncan@umd.edu

Prof. R. W. Griffiths, Research School of Earth Sciences, Australian National University, Building 61, Canberra, ACT 0200, Australia.
Ross.Griffiths@anu.edu.au

Prof. D. S. Henningson, KTH Mechanics, SE-10044 Stockholm, Sweden. jfm@mech.kth.se

Prof. Y. Kaneda, Department of Computational Science and Engineering, Nagoya University, Chikusa-ku, Nagoya, Aichi 464-8603, Japan.
kaneda@cse.nagoya-u.ac.jp

Prof. J. C. Lasheras, University of California, San Diego, 9500 Gillman Drive, La Jolla, CA 92093-0411, USA. lasherasjfm@eng.ucsd.edu

Prof. D. Lohse, Physics of Fluids Group, Department of Applied Physics, Faculty of Science, University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands. lohse.jfm@tnw.utwente.nl

Prof. J. Magnaudet, Institut de Mécanique des Fluides de Toulouse, Allée Camille Soula, 31400 Toulouse, France. magnau.jfm@imft.fr

Prof. I. Marusic, Department of Mechanical Engineering, University of Melbourne, VIC 3010, Australia. imarusic@unimelb.edu.au

Prof. M. Matalon, Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign, 1206 West Green Street, Urbana, IL 61801, USA. matalon@illinois.edu

Prof. O. Pouliquen, IUSTI, CNRS - Aix Marseille University, 5 rue Enrico Fermi, 13453 Marseille CEDEX 13, France.
pouliquen.jfm@polytech.univ-mrs.fr

Prof. J. J. Riley, Department of Mechanical Engineering, Box 352600, University of Washington, Seattle, WA 98195, USA.
rileyj@u.washington.edu

Prof. R. Verzicco, Università di Roma ‘Tor Vergata’, Dipartimento di Ingegneria Meccanica, via del Politecnico 1, 00133 Roma, Italy.
verzicco.JFM@uniroma2.it

RAPIDS EDITOR

Prof. P. F. Linden, Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Centre for Mathematical Sciences, Wilberforce Road, Cambridge CB3 0WA, UK. p.f.linden@damtp.cam.ac.uk

RAPIDS ASSOCIATE EDITORS

Prof. É. Guazzelli, IUSTI CNRS - Aix Marseille University, 5 rue Enrico Fermi, 13453 Marseille CEDEX 13, France. guazzelli.jfm@polytech.univ-mrs.fr

Prof. N. Peake, DAMTP, University of Cambridge, Centre for Mathematical Sciences, Wilberforce Road, Cambridge CB3 0WA, UK. N.Peake@damtp.cam.ac.uk

Prof. J. S. Wettlaufer, Mathematical Institute, University of Oxford, Radcliffe Observatory Quarter, Woodstock Road, Oxford OX2 6GG, UK. jfm@yale.edu

EDITORIAL OFFICE

FAX 44 1223 325802; JFMproduction@cambridge.org

SUMMARY OF INSTRUCTIONS FOR AUTHORS

Full instructions are available on the JFM web page at <http://www.jfm.damtp.cam.ac.uk>

Submission

Authors wishing to have papers published in the *Journal* should submit them via the online submission and refereeing system, Manuscript Central, at <http://mc.manuscriptcentral.com/cup/jfm>. Papers may be submitted to any editor or associate editor but JFM Rapids articles (10 printed pages or fewer) must be submitted to Professors Linden, Guazzelli, Peake or Wettlaufer who should be consulted in advance. Submission of a paper implies a declaration by the author that the work is not being considered for publication elsewhere and that it has not already been considered by a different editor of the *Journal*. Conference Reports must be submitted within three months of the meeting.

Preparation of papers

Authors are encouraged to write their papers clearly, concisely and attractively, so that their work will be readily understood. A brief summary of editorial requirements for notation, English and presentation is available on the JFM web page (address above). Authors are urged to use the JFM latex style macros. The [referee] option should be used for initial submission. The style file and template files are available at http://journals.cambridge.org/JFM_submission. While use of the JFM latex style file is preferred (and note that this is mandatory for JFM Rapids submissions), ordinary latex or plain tex files can also be accepted. Other software, such as Word, will be converted to latex by the Press or retyped. Manuscripts not prepared using the JFM latex style file should be typed in double spacing, with references listed at the end in alphabetical order of authors and with a separate list of figure captions.

Extensive detailed mathematical relations, tables or figures likely to be useful only to a few specialists will not be printed, but will be available as an electronic supplement to the online version or from the JFM Editorial Office.

Movies

Refereed movies that are integral to a paper can be supplied during the submission process and will be published as supplementary materials.

Accepted papers

Once a paper is accepted, final production files (e.g. the LaTeX source) must be uploaded to the Manuscript Central site. Full details are given on the JFM web page. Do not email files to the JFM Editorial Office unless requested to do so.

Charges

There is no charge for publication, but the cost of any colour figures in standard articles must be borne by authors. Authors will receive a PDF file of their published article via email. For standard articles only, offprints can be purchased if ordered when the proofs are returned.

Address questions or comments to Mrs Amanda Johns (Editorial Assistant) or Mrs Alison James (Production Editor) at the Journals Department, Cambridge University Press, Shaftesbury Road, Cambridge CB2 8RU, UK; tel: 44 (0)1223 347922; fax: 44 (0)1223 325802; e-mail: JFMproduction@cambridge.org.