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A pressure-based algorithm for multi-phase flow at all speeds. (English) Zbl 1076.76074

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Summary: A new finite volume-based numerical algorithm for predicting incompressible and compressible multi-phase flow phenomena is presented. The technique is equally applicable in the subsonic, transonic, and supersonic regimes. The method is formulated on a non-orthogonal coordinate system in collocated primitive variables. Pressure is selected as a dependent variable in preference to density because changes in pressure are significant at all speeds as opposed to variations in density, which become very small at low Mach numbers. The pressure equation is derived from overall mass conservation. The performance of the new method is assessed by solving the following two-dimensional two-phase flow problems: (i) incompressible turbulent bubbly flow in a pipe, (ii) incompressible turbulent air-particle flow in a pipe, (iii) compressible dilute gas-solid flow over a flat plate, and (iv) compressible dusty flow in a converging diverging nozzle. Predictions are shown to be in excellent agreement with published numerical and/or experimental data.

MSC:

76T30 Three or more component flows
76M12 Finite volume methods applied to problems in fluid mechanics

Keywords:

Multi-phase flow; Pressure-based algorithm; All speed flows; Finite volume method

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References:

[1] Brandt, A., Multi-level adaptive solutions to boundary-value problems, Math. comp., 31, 333-390, (1977) · Zbl 0373.65054

[2] C.M. Rhie, A pressure based Navier-Stokes solver using the multigrid method, AIAA Paper 86-0207, 1986

[3] P. Wesseling, An Introduction to Multigrid Methods, Wiley, Baffins Lane, Chichester, West Sussex PO19 1UD, UK, 1995 · Zbl 0760.65092

[4] Dick, E., Multigrid formulation of polynomial flux-difference splitting for steady Euler equations, J. comput. phys., 91, 161-173, (1990) · Zbl 0711.76069

[5] Kershaw, D., The incomplete Cholesky-conjugate gradient method for the iterative solution of systems of linear equations, J. comput. phys., 26, 43-65, (1978) · Zbl 0367.65018

[6] Stone, H.L., Iterative solution of implicit approximations of multidimensional partial differential equations, SIAM J. numer. anal., 5, 3, 530-558, (1968) · Zbl 0197.13304

[7] V. Venkatakrishnan, D.J. Mavriplis, Implicit method for the computation of unsteady flows on unstructured grids, AIAA Paper 95-1705, 1995 · Zbl 0862.76054

[8] Venkatakrishnan, V., Perspective on unstructured grid solvers, Aiaa j., 34, 3, 533-547, (1996) · Zbl 0896.76002

[9] D.L. Whitaker, Three dimensional unstructured grid Euler computations using a fully-implicit, upwind method, AIAA Paper 93-3357, 1993

[10] Oan, D.; Cheng, J.C., Upwind finite volume navier – stokes computations on unstructured triangular meshes, Aiaa j., 31, 9, 1618-1625, (1993) · Zbl 0783.76078

[11] C.R. Mitchell, Improved reconstructuion schemes for the Navier-Stokes equations on unstructured grids, AIAA Paper 94-0642, 1994

[12] T.J. Barth, D.C. Jespersen, The design and application of upwind schemes on unstructured meshes, AIAA Paper 89-0366, January 1989

[13] Gaskell, P.H.; Lau, A.K.C., Curvature compensated convective transport: SMART, a new boundedness preserving transport algorithm, Int. J. numer. methods fluids, 8, 617-641, (1988) · Zbl 0668.76118

[14] Leonard, B.P., Locally modified quick scheme for highly convective 2-D and 3-D flows, (), 35-47

[15] Darwish, M.S.; Moukalled, F., Normalized variable and space formulation methodology for high-resolution schemes, Numer. heat transfer, part B, 26, 79-96, (1994)

[16] Moukalled, F.; Darwish, M.S., A new family of streamline-based very high resolution schemes, Numer. heat transfer, 32, 3, 299-320, (1997)

[17] Darwish, M.; Moukalled, F., An efficient very high-resolution scheme based on an adaptive-scheme strategy, Numer. heat transfer, part B, 34, 191-213, (1998)

[18] Moukalled, F.; Darwish, M., New family of adaptive very high resolution schemes, Numer. heat transfer, part B, 34, 215-239, (1998)

[19] Marchi, C.H.; Maliska, C.R., A non-orthogonal finite-volume methods for the solution of all speed flows using co-located variables, Numer. heat transfer, part B, 26, 293-311, (1994)

[20] Demirdzic, I.; Lilek, Z.; Peric, M., A collocated finite volume method for predicting flows at all speeds, Int. J. numer. methods fluids, 16, 1029-1050, (1993) · Zbl 0774.76066

[21] Lien, F.S.; Leschziner, M.A., A general non-orthogonal collocated finite volume algorithm for turbulent flow at all speeds incorporating second-moment turbulence-transport closure, part 1: computational implementation, Comput. methods appl. mech. eng., 114, 123-148, (1994)

[22] Politis, E.S.; Giannakoglou, K.C., A pressure-based algorithm for high-speed turbomachinery flows, Int. J. numer. methods fluids, 25, 63-80, (1997) · Zbl 0882.76057

[23] Chen, K.H.; Pletcher, R.H., Primitive variable, strongly implicit calculation procedure for viscous flows at all speeds, Aiaa j., 29, 8, 1241-1249, (1991)

[24] Darbandi, M.; Shneider, G.E., Momentum variable procedure for solving compressible and incompressible flows, Aiaa j., 35, 12, 1801-1805, (1997) · Zbl 0908.76050

[25] M. Darbandi, G.E. Schneider, Use of a flow analogy in solving compressible and incompressible flows, AIAA Paper 97-2359, January 1997

[26] K.C. Karki, A calculation procedure for viscous flows at all speeds in complex geometries, Ph.D. Thesis, University of Minnesota, June 1986

[27] Moukalled, F.; Darwish, M., A high-resolution pressure-based algorithm for fluid flow at all speeds, J. comput. phys., 168, 1, 101-133, (2001) · Zbl 0991.76047

[28] Patankar, S.V.; Spalding, D.B., A calculation procedure for heat, mass and momentum transfer in three dimensional parabolic flows, Int. J. heat mass transfer, 15, 1787, (1972) · Zbl 0246.76080

[29] S.V. Patankar, Numerical Heat Transfer and Fluid Flow, Hemisphere, Washington DC, 1981 · Zbl 0521.76003

[30] R.I. Issa, Solution of the implicit discretized fluid flow equations by operator splitting, Mechanical Engineering Report, FS/82/15, Imperial College, London, 1982

[31] Van Doormaal, J.P.; Raithby, G.D., Enhancement of the SIMPLE method for predicting incompressible fluid flows, Numer. heat transfer, 7, 147-163, (1984) · Zbl 0553.76005

[32] J.P. Van Doormaal, G.D. Raithby, An evaluation of the segregated approach for predicting incompressible fluid flows, ASME Paper 85-HT-9, Presented at the National Heat Transfer Conference, Denver, CO, August 4-7, 1985

[33] Acharya, S.; Moukalled, F., Improvements to incompressible flow calculation on a non-staggered curvilinear grid, Numer. heat transfer, part B, 15, 131-152, (1989) · Zbl 0694.76019

[34] C.R. Maliska, G.D. Raithby, Calculating 3-D fluid flows using non-orthogonal grid, Proc. Third Int. Conf. on Numerical Methods in Laminar and Turbulent Flows, Seattle, 1983, pp. 656-666 · Zbl 0554.76027

[35] Moukalled, F.; Darwish, M., A unified formulation of the segregated class of algorithms for fluid flow at all speeds, Numer. heat transfer, part B, 37, 1, 103-139, (2000)

[36] Darwish, M.; Moukalled, F.; Sekar, B., A unified formulation of the segregated class of algorithms for multi-fluid flow at all speeds, Numer. heat transfer, part B, 40, 2, 99-137, (2001)

[37] D.B. Spalding, The Calculation of free-convection phenomena in gas-liquid mixtures, Report HTS/76/11, Mech. Eng. Imperial College, London, 1976

[38] Spalding, D.B., Numerical computation of multi-phase fluid flow and heat transfer, (), 139-167

[39] D.B. Spalding, A general purpose computer program for multi-dimensional, one and two phase flow, Report HTS/81/1, Mech. Eng. Imperial College, London, 1981

[40] W.W. Rivard, M.D. Torrey, KFIX: A program for transient two dimensional two fluid flow, Report LA-NUREG-6623, 1978

[41] A.A. Amsden, F.H. Harlow, KACHINA: An Eulerian computer program for multifield flows, Report LA-NUREG-5680, 1975

[42] A.A. Amsden, F.H. Harlow, KTIFA two-fluid computer program for down comer flow dynamics, Report LA-NUREG-6994, 1977

[43] B.S. Baldwin, H. Lomax, Thin Layer approximation and algebraic model for separated turbulent flows, AIAA Paper 78-257, 1978

[44] Sotiropoulos, F.; Patel, V.C., Application of Reynolds-stress transport models to stern and wake flow, J. ship res., 39, 263, (1995)

[45] D. Cokljat, V.A. Ivanov, F.J. Srasola, S.A. Vasquez, Multiphase \textit{k}-ε models for unstructured meshes, ASME 2000

Fluids Engineering Division Summer Meeting, June 11-15, 2000, Boston, MA, USA

[46] Pourahmadi, F.; Humphrey, J.A.C., Modeling solid – fluid turbulent flows with application to predicting erosive wear, Int. J. phys. chem. hydro., 4, 191-219, (1983)

[47] Elghobashi, S.E.; Abou-Arab, T.W., A two-equation turbulence model for two-phase flows, Phys. fluids, 26, 4, 931-938, (1983) · Zbl 0564.76098

[48] Chen, C.P.; Wood, P.E., Turbulence closure modeling of the dilute gas – particle axisymmetric jet, Aiche j., 32, 1, 163-166, (1986)

[49] Lopez de Bertodano, M.; Lee, S.J.; Lahey, R.T.; Drew, D.A., The prediction of two-phase turbulence and phase distribution phenomena using a Reynolds stress model, ASME J. fluids eng., 112, 107-113, (1990)

[50] Lopez de Bertodano, M.; Lahey, R.T.; Jones, O.C., Development of a \textit{k}-ε model for bubbly two-phase flow, ASME J. fluids eng., 116, 128-134, (1994) · Zbl 1134.76524

[51] Lopez de Bertodano, M.; Lahey, R.T.; Jones, O.C., Phase distribution in bubbly two-phase flow in vertical ducts, Int. J. multiphase flow, 20, 5, 805-818, (1994) · Zbl 1134.76524

[52] A. Serizawa, I. Kataoka, I. Michiyoshi, Phase distribution in bubbly flow, Data set No. 24, Proc. Second Int. Workshop on Two-Phase Flow Fundamentals, Rensselaer Polytechnic Institute, Troy, NY, 1986

[53] Wang, S.K.; Lee, S.-j.; Jones, O.C.; Lahey, R.T., 3-D turbulence structure and phase distribution measurements in bubbly two-phase flows, Int. J. multiphase flow, 13, 3, (1987)

[54] Antal, S.P.; Lahey, R.T.; Flaherty, J.E., Analysis of phase distribution in fully developed laminar bubbly two-phase flows, Int. J. multiphase flow, 17, 5, 635-652, (1991) · Zbl 1134.76479

[55] Y. Sato, M. Sadatomi, K. Sekoguchi, Momentum and heat transfer in two-phase bubble flow, in: International Journal of Multiphase Flow, I. Theory, pp. 167-177. II. A Comparison Between Experiment and Theoretical Calculations, 1981, pp. 179-190 · Zbl 0467.76093

[56] Lopez de Bertodano, M.; Lee, S.-J.; Lahey, R.T.; Drew, D.A., The prediction of two-phase turbulence and phase distribution phenomena using a Reynolds stress model, J. fluids eng., 112, 107-113, (1990)

[57] Lopez de Bertodano, M.; Lahey, R.T.; Jones, O.C., Development of a \textit{k}-ε model for bubbly two-phase flow, J. fluids eng., 116, 128-134, (1994) · Zbl 1134.76524

[58] Lopezde Bertodano, M.; Lahey, R.T.; Jones, O.C., Phase distribution in bubbly two-phase flow in vertical ducts, Int. J. multiphase flow, 20, 5, 805-818, (1994) · Zbl 1134.76524

[59] Nakoryakov, V.E.; Kashinsky, O.N.; Randin, V.V.; Timkin, L.S., Gas – liquid bubbly flow in vertical pipes, J. fluids eng., 118, 377-382, (1996)

[60] Boisson, N.; Malin, M.R., Numerical prediction of two-phase flow in bubble columns, Int. J. numer. methods fluids, 23, 1289-1310, (1996) · Zbl 0892.76083

[61] B. Huang, Modelisation Numerique D'ecoulements Diphasiques a Bulles dans les Reacteurs Chimiques, Ph.D. Thesis, Universite Claude Bernard, Lyon, 1989

[62] K.O. Peterson, Etude Experimentale et Numerique des Ecoulements Diphasiques dans les Reacteurs Chimiques, Ph.D. Thesis, Universite Claude Bernard, Lyon, 1992

[63] Lahey, R.T.; Lopez de Bertodano, M.; Jones, O.C., Phase distribution in complex geometry ducts, Nuclear eng. design, 141, 177, (1993)

[64] Drew, D.A.; Lahey, T.J., The virtual mass and lift force on a sphere in rotating and straining inviscid flow, Int. J. multiphase flow, 13, 1, 113, (1987) · Zbl 0627.76014

[65] PHOENICS: "http://www.cham.co.uk/phoenics/d_polis/d_applic/d_flows/laheya.htm"

[66] Tsuji, Y.; Morikawa, Y.; Shiomi, H., LDV measurements of an air – solid two-phase flow in a vertival pipe, J. fluid mech., 139, 417-434, (1984)

[67] Adeniji-Fashola, A.; Chen, C.P., Modeling of confined turbulent fluid-particle flows using eulerian and Lagrangian schemes, Int. J. heat mass transfer, 33, 691-701, (1990)

[68] Naik, S.; Bryden, I.G., Prediction of turbulent gas – solids flow in curved ducts using the eulerian – lagrangian method, Int. J. numer. methods fluids, 31, 579-600, (1999) · Zbl 0962.76625

[69] Harlow, F.H.; Amsden, A.A., Numerical calculation of multiphase fluid flow, J. comput. phys., 17, 19-52, (1975) · Zbl 0297.76079

[70] Osiptsov, A.N., Structure of the laminar boundary layer of a disperse medium on a flat plate, Fluid dynamics, 15, 512-517, (1980) · Zbl 0461.76054

[71] Prabha, S.; Jain, A.C., On the use of compatibility conditions in the solution of gas particulate boundary layer equations, Appl. sci. res., 36, 81-91, (1980) · Zbl 0445.76088

[72] Sgleton, R.E., The incompressible gas solid particle flows over a semi-infinite flat plate, Z. angew. math. phys., 19, 545, (1965)

[73] Wang, B.Y.; Glass, I.I., Compressible laminar boundary layer flows of a dusty gas over a semi-infinite flat plate, J. fluid mech., 186, 223-241, (1988) · Zbl 0643.76082

[74] S.L. Soo, Boundary layer motion of a gas – solids suspension, in: Proc. Symp. Interaction Between Fluids and Particles, Inst. Chem. Eng., 1962, pp. 50-63

[75] Chamkha, A.J.; Peddieson, J.J.R., Boundary layer flow of a particulate suspension past a flat plate, Int. J. multiphase flow, 17, 805-808, (1991)

[76] Thevand, N.; Daniel, E.; Loraud, J.C., On high-resolution schemes for solving unsteady compressible two-phase dilute viscous flows, Int. J. numer. methods fluids, 31, 681-702, (1999) · Zbl 0952.76062

[77] Chang, I.S., One and two-phase nozzle flows, Aiaa j., 18, 1455-1461, (1980)

[78] Ishii, R.; Kawasaki, K., Limiting particle streamline in the flow of a gas – particle mixture through an axially symmetric nozzle, Phys. fluids, 25, 6, 959-966, (1982) · Zbl 0498.76090

[79] Ishii, R.; Umeda, Y.; Kawasaki, K., Nozzle flows of gas – particle mixtures, Phys. fluids, 30, 3, 752-760, (1987)

[80] Hwang, C.J.; Chang, G.C., Numerical study of gas – particle flow in a solid rocket nozzle, Aiaa j., 26, 6, 682-689, (1988)

[81] Chang, H.T.; Hourng, L.W.; Chien, L.E., Application of flux-vector-splitting scheme to a dilute gas – particle JPL nozzle flow, Int. J. numer. methods fluids, 22, 921-935, (1996) · Zbl 0863.76040

[82] Mehta, R.C.; Jayachandran, T., A fast algorithm to solve viscous two-phase flow in an axisymmetric rocket nozzle, Int. J. numer. methods fluids, 26, 501-517, (1998) · Zbl 0921.76110

[83] Igra, O.; Elperin, I.; Ben-Dor, G., Dusty gas flow in a converging – diverging nozzle nozzle, J. fluids eng., 121, 908-913, (1999)

[84] Back, L.H.; Cuffel, R.F., Detection of oblique shocks in a conical nozzle with a circular-arc throat, Aiaa j., 4, 2219-2221, (1966)

[85] Back, L.H.; Massier, P.F.; Cuffel, R.F., Flow phenomena and convective heat transfer in a conical supersonic nozzle, J. spacecraft, 4, 1040-1047, (1967)

[86] Cuffel, R.F.; Back, L.H.; Massier, P.F., Transonic flowfield in a supersonic nozzle with small throat radius of curvature, Aiaa j., 7, 1364-1366, (1969)