DATA REDUCTION METHOD FOR STEAM FLOW FIELDS

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ABSTRACT

The paper deals with data reduction method developed for steam flows. The method is based on conservation laws – balances of mass, momentum, and energy fluxes. Thermodynamic properties of steam according to the IAPWS-IF97 formulation are applied. The data reduction method is described and discussed.

INTRODUCTION

Data reduction systems belong to a needful software equipment of aerodynamic laboratories. They are applied for solution of reference parameters of flow. The correct system has to be based on the conservation equations for mass, momentum, and energy, and is supplemented by equation of state. Consequently both the flow data and the homogeneous data are equivalent with respect to the conservative physical properties. The data reduction method has been developed originally for an ideal gas. The data reduction method was presented in [1] and the method was developed for more general cases. For example, total temperature distribution was approved in [2] and distribution of concentration of another injected gas was presented in [3]. Analysis of the reduction method was performed in [3] and its range of valid arguments was derived. The existence of limits of valid arguments is connected with occurrence of effects at compressible fluid flow. They are - existence of maximum mass flux, existence of maximum velocity of gas flow, existence of limit load, existence of shock waves in compressible fluid flow field, etc. Further analysis in [4] proved conditions for flow parameters determined from double solution of the system of equations of the data reduction method. However, the system of [1] to [4] is based on theory of an ideal gas.

In this paper authors intend to present the data reduction method for steam flow fields. The complex relations between thermodynamic parameters of steam are the reason that equation of state of ideal gas cannot be applied. In [5] data reduction method was extended for solution of two-dimensional steady flow fields of steam. Thermodynamic properties of steam according to the IAPWS-IF97 formulation [6] are recommended for this purpose. The data reduction method for steam flow fields is described in this paper and ranges of valid arguments entering into solution of reduced data [7] will be shown.

NOMENCLATURE

p	pressure, Pa
a	speed of sound, $m.s^{-1}$
ρ	density, $kg.m^{-3}$
T	temperature, K
κ	ratio of heat capacities (Poisson constant), dimensionless
r	specific gas constant, $J.kg^{-1}.K^{-1}$
v	velocity, $m.s^{-1}$
h	specific enthalpy, $kJ.kg^{-1}$
s	specific entropy, $kJ.kg^{-1}.K^{-1}$
α	angle, °
x	dryness fraction, dimensionless
y	distance coordinate, m

DATA REDUCTION METHOD FOR TWO-DIMENSIONAL FLOW FIELD OF STEAM

Let us have a line y in two-dimensional flow of steam according to Fig.1. On the line, abscissa |0T| is an infinitesimal control volume having its length t. Upstream of this volume are distributions of pressure $p(y)$, density $\rho(y)$ and velocity vector (i.e. distribution of flow angle $\alpha(y)$ of velocity vector oriented to normal of abscissa |0T| and of absolute value of velocity vector $v(y)$) of flowing steam along abscissa |0T|. Let there are given distributions of pressure $p(y)$, density $\rho(y)$ and angle $\alpha(y)$. It is possible to obtain distribution of specific enthalpy $h(y)$ by means of the IAPWS-IF97 from $p(y)$ and $\rho(y)$. Distribution of absolute value of velocity vector $v(y)$ is solved when the assumption of constant total specific enthalpy $h_0(y) = h_0$ = given constant.

The aim of the data reduction method is to solve homogeneous values of parameters pressure p, density ρ, specific enthalpy h, absolute value of velocity vector v and angle α downstream of the control volume.

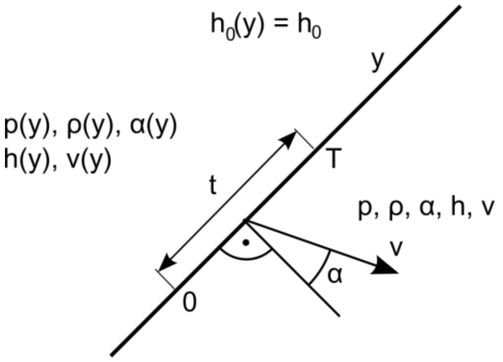

Fig. 1: Parameters for two-dimensional steam flow.

The principle of the data reduction method is to solve conservation equations of mass, momentum, and energy. Consequently integrals of mass flux I_M, of momentum flux I_A in normal direction to infinitesimal control volume (to abscissa |0T|), and momentum flux I_C in circumferential direction to control volume.

$$I_M = \frac{1}{t}\int_0^t \rho(y)v(y)\cos\alpha(y)dy \tag{1}$$

$$I_A = \frac{1}{t}\int_0^t \left[\rho(y)v^2(y)\cos^2\alpha(y) + p(y)\right]dy \tag{2}$$

$$I_C = \frac{1}{t}\int_0^t \rho(y)v^2(y)\sin\alpha(y)\cos\alpha(y)dy \tag{3}$$

Integrals I_M, I_A, and I_C will be applied to calculations of arguments of the data reduction method. The balance equations have integrals I_M, I_A, and I_C on their right sides.

Mass:

$$\rho \cdot v \cdot \cos\alpha = I_M \tag{4}$$

Momentum normal to y:

$$\rho \cdot v^2 \cdot \cos^2\alpha + p = I_A \tag{5}$$

Momentum in direction of y:

$$\rho \cdot v^2 \cdot \cos\alpha \cdot \sin\alpha = I_C \tag{6}$$

Energy:

$$h_0(y) = h_0 = h(y) + \frac{v^2(y)}{2} \tag{7}$$

Equation of state of steam:

$$h_{IAPWS-IF97} = f_h(p, \rho) \tag{8}$$

Of course, equation of state Eq.(8) holds both locally and globally. The system of equations, Eqs. (4) to (8), is a mathematical basis of the data reduction method and its solution determines reduced parameters. For ideal gas the system of equations, Eqs. (4) to (7), supplemented with equation of state

$$h = \frac{\kappa - 1}{\kappa}\frac{p}{\rho} \tag{10}$$

is modified into non dimensional form and reduced parameters can be solved analytically [3]. κ is ratio of heat capacities. For steam flows the system of equations, Eqs. (4) to (8), can be solved by means of iterative numerical procedure.

In the first iterative step, the value of specific enthalpy h is chosen. Then the pressure $p(h)$ and density $\rho(h)$ are solved from following equations derived from conservation equations.

$$p(h) = I_A - I_M\sqrt{2(h_0 - h) - \left(\frac{I_C}{I_M}\right)^2} \tag{9}$$

$$\rho(h) = \frac{I_M}{\sqrt{2(h_0 - h) - \left(\frac{I_C}{I_M}\right)^2}} \tag{10}$$

By means of the IAPWS-IF97, the specific enthalpy $h_{\text{IAPWS-IF97}}$ is determined

$$h_{IAPWS-IF97}(h) = f_h(p(h), \rho(h)) \tag{11}$$

and then it is consequently applied in Eq. (5) for the following iterative step until:

$$h_{IAPWS-IF97} = h \tag{12}$$

Iterative procedure seems to be fast. A graphical aid can help to find solutions of the system of conservative equations supplemented with equation of state for steam when diagram with curves of $h = f(p)$ dependency and $h_{IAPWS-IF97} = f(p)$. Points of intersection determine approximately the solution being sought. It is shown that two solutions of specific enthalpy h and the corresponding pressure p exist. It is essential having an experience to determine proper solution.

The final calculation of values of the thermodynamic and flow parameters is performed by means of IAPWS data and system of equations from data reduction method:

Density

$$\rho = f_\rho(p, h) \tag{13}$$

Velocity

$$v = \sqrt{(I_A - p)^2 + I_C^2} \Big/ I_M \tag{14}$$

Flow angle

$$\alpha = \arcsin\left(I_C / (I_M v)\right) \tag{15}$$

Temperature

$$T = f_T(p, h) \tag{16}$$

Specific entropy

$$s = f_s(p, h) \tag{17}$$

Speed of sound

$$a = f_a(p, T) \tag{18}$$

Total pressure

$$p_0 = f_p(s, h_0) \tag{19}$$

Total temperature

$$T_0 = f_T(p_0, h_0) \tag{20}$$

Dryness of steam

$$x = f_x(p, h) \tag{21}$$

RANGES OF VALID ARGUMENTS FOR DATA REDUCTION METHOD IN STEAM FLOW

The ranges of valid arguments for ideal gas flows fields were analytically derived in [3] and are expressed in diagram $\left(\frac{I_C}{\tilde{I}_M}\right)^2 - \left(\frac{I_A}{\tilde{I}_M}\right)^2$. I_C and I_A are modified integrals from balances of momentum fluxes in peripheral and axial directions, respectively. $\tilde{I}_M$ is modified integral from balance of mass flux. The ranges of valid arguments for ideal gas are presented in Fig.1. Further analysis in [4] proved the ranges of valid arguments and moreover determined dependencies of reduced flow parameters.

Determination of the ranges of valid arguments for data reduction method in steam flow fields analytically is very difficult due to complex state equation of steam. The authors proposed [7] a numerical approach of mapping of large number of state calculations presented in diagrams $\left(\frac{I_C}{I_M \cdot a_0}\right)^2 - \left(\frac{I_A}{I_M \cdot a_0}\right)^2$. Arguments I_M, I_A, and I_C are solved from Eqs. (4), (5), and (6).

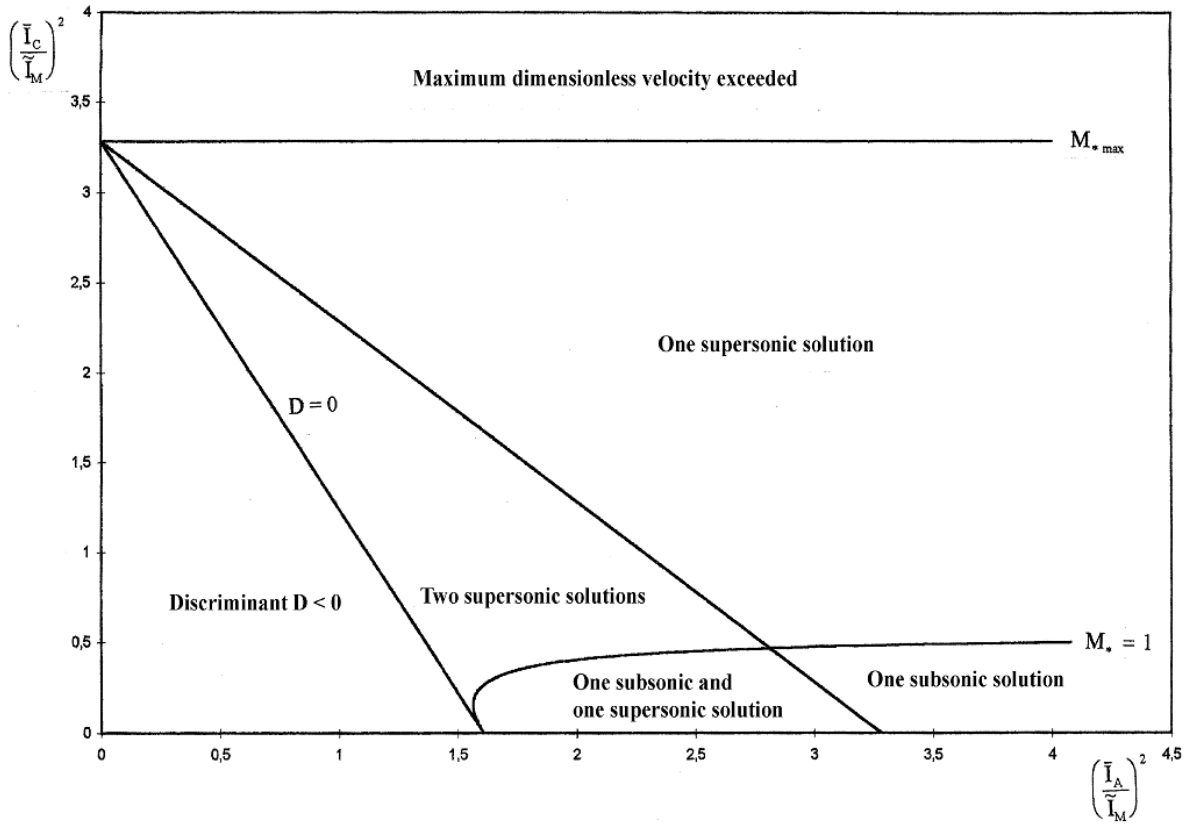

Fig.2: Ranges of valid arguments for data reduction method in an ideal gas flow [4].

Calculations were performed for total specific enthalpy h_0 = 3000 kJ/kg. Thermodynamic parameters – specific enthalpy h and specific entropy s were chosen. Pressure p, density ρ, and speed of sound at total conditions a_0 were solved by means of the IAPWS-IF97 formulation [5].

Velocities were solved from Eq. (8) by:

$$v = \sqrt{2(h_0 - h)} \tag{22}$$

The angles α were chosen. Achieved results are presented in diagrams in Figs. 3 and 4 where envelopes of the depicted curves determine the range of valid arguments for data reduction method in steam flow fields.

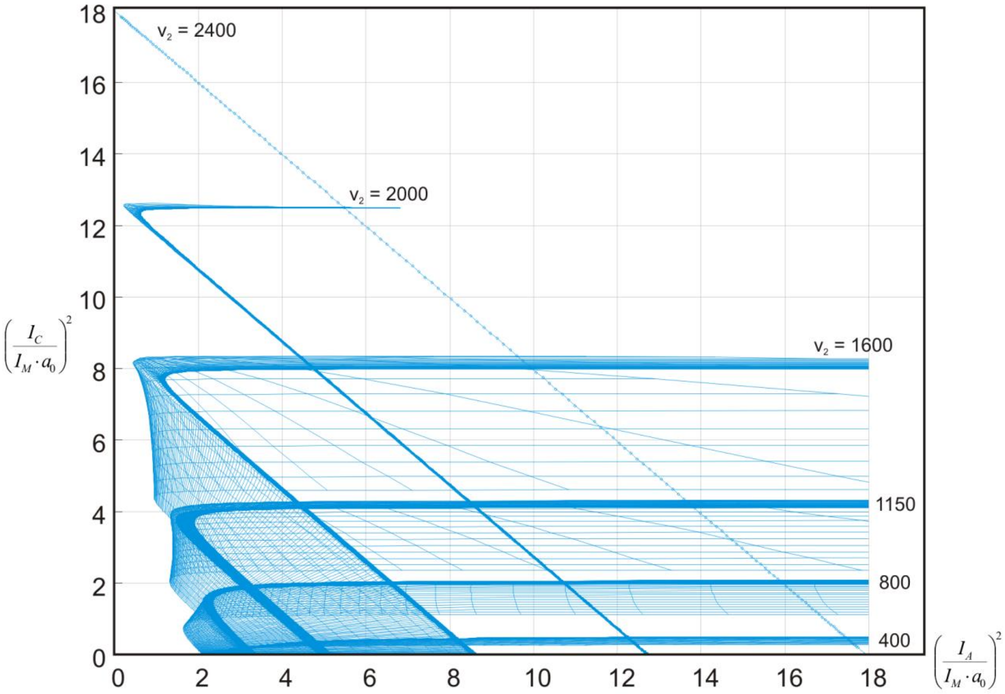

Fig. 3: Dependencies of arguments of data reduction method in steam flow field, velocities, v [m/s] = const.

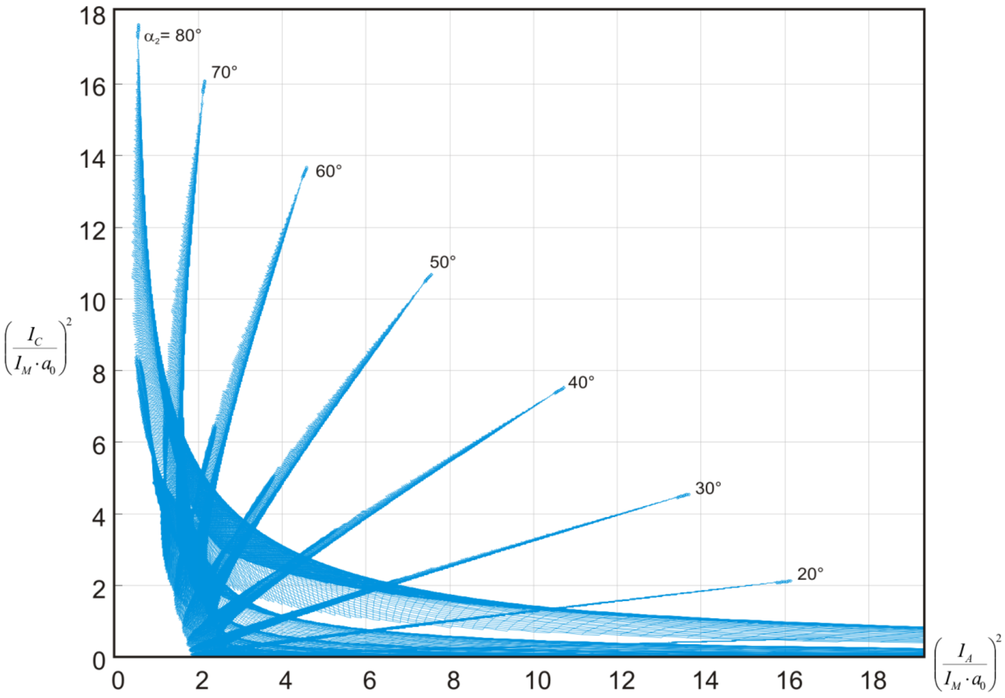

Fig. 4: Dependencies of arguments of data reduction method in steam flow field, flow angles, α [°] = const.

APPLICATION OF DATA REDUCTION METHOD FOR TWO-DIMENSIONAL FLOW FIELDS OF STEAM

Five sets of data have been prepared [5] as a task for verification of the data reduction method in team flow field. Calculations were performed for total specific enthalpy $h_0 = 3100$ kJ/kg.

Results are shown in Fig. 5 and they are also shown in Table 1 along with relative uncertainties of the calculations. Very close values of the 1st and 2nd solutions for the task No. 3 are remarkable. Values of uncertainties higher than 1% prove the solution not to be the proper one or the need to be analyzed in more detail. Proper solution has the values of uncertainties lower than 0.1%.

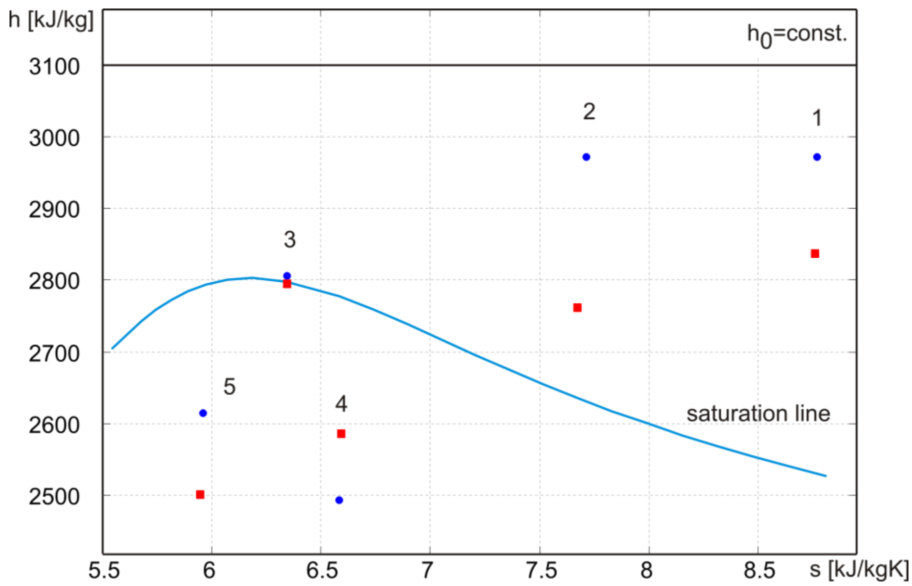

Fig.5: Results from data reduction method for two-dimensional steam flow. (Number denotes number of task, blue points 1st solution, red squares 2nd solution).

Inputs		Task No.									
		1		2		3		4		5	
h_0[J/kg]	given	3100000		3100000		3100000		3100000		3100000	
I_M		36.54		322.61		4967.40		688.52		3745.90	
I_A		36025		324900		4467500		579250		3262800	
I_C		9252		104800		2940600		656880		3469600	
Results		result	relative uncertainty	result	relative uncertainty	result	relative uncertainty	result	relative uncertainty	result	relative uncertainty
p [Pa]	1st solution	19994	0.00030	199980	0.00010	2040100	-0.02005	200090	-0.00045	2000300	-0.00015
h [J/kg]		2971700	0.00003	2972300	0.00000	2805400	-0.00143	2493300	-0.00004	2614200	0.00000
ρ [kg/m^3]		0.08330	0.00035	0.83317	0.00020	10.16500	-0.01650	1.25030	-0.00024	11.11400	-0.00026
v [m/s]		506.49	-0.00026	505.43	-0.00012	767.63	0.00667	1101.60	0.00003	985.67	0.00003
α [rad]		0.5235	0.00028	0.6980	0.00015	0.8807	-0.00923	1.0473	-0.00010	1.2218	-0.00006
s [J/kgK]		8770.80	-	7712.00	-	6345.40	-	6585.30	-	5959.80	-
p [Pa]	2nd solution	11190	0.44050	81220	0.59390	1944900	0.02755	343100	-0.71550	1080500	0.45975
h [J/kg]		2837000	0.04536	2762000	0.07075	2795800	0.00200	2586100	-0.03726	2501300	0.04319
ρ [kg/m^3]		0.05377	0.35474	0.42712	0.48746	9.78150	0.02185	2.00740	-0.60592	6.42960	0.42134
v [m/s]		725.23	-0.43224	822.21	-0.62694	779.97	-0.00929	1013.80	0.07973	1094.20	-0.11008
α [rad]		0.3566	0.31891	0.4062	0.41822	0.8618	0.01248	1.2257	-0.17046	1.0093	0.17388
s [J/kgK]		8760.80	-	7675.10	-	6345.40	-	6594.30	-	5947.60	-

Tab.1: Results from data reduction method for two-dimensional steam flow.

RESULTS and DISCUSSION

The data reduction method is extended for solution parameters of two-dimensional flow fields of steam. The method is based on mass, momentum and energy balance equations, and on equation of state of steam IAPWS-IF97. Solution of system of equations was prepared and verified. Further development of the data reduction method will continue.

Distributions of parameters of experimental data from sections of steam flow field are used for evaluation of balance integrals. Then the system of conservation equations supplemented with equation of state for steam (enthalpy calculated $h_{IAPWS\_IF97} = f_h(p, \rho)$, p is pressure, ρ is density) is solved by means of iterative numerical procedure. Results by means of data reduction method for steam flows are solved and presented. Proper solution has the values of uncertainties lower than 0.1%.

Range of valid arguments for data reduction method in the steam flow can be determined and is presented (see Figs.3 and 4). Arguments are solved from quantities: I_M is balance integral of mass flux, I_A is balance integral of momentum flux in axial direction, I_C is balance integral of momentum flux in circumferential direction, a_0 is speed of sound at stagnation conditions.

In the region of transonic and supersonic velocities, the system of conservation equations has two solutions. Identification the correct solution should be studied. Achieved results, and further development and applications of the developed method are the basis for further discussions and development of the data reduction method.

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