ON EVALUATION OF STEAM FLOW PARAMETERS FROM EXPERIMENTAL OR NUMERICAL DATA DISTRIBUTION ON TRAVERSE PLANE

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Abstract

The paper deals with data reduction method for evaluation of the steam flow parameters. Integrals of mass flux and momentum flux are solved from experimental or numerical data distribution on the traverse plane. Balance equations of mass, momentum and energy, supplemented by equation of state of steam according to IAPWS-IF97, are forming the system of equations. The solution is performed using iterative procedure. The application of the data reduction method is presented and analysis of achieved results is performed.

Keywords: Data reduction method, steam flow, IAPWS-IF97

1 Introduction

Data reduction systems belong to a needful software equipment of aerodynamic laboratories. They are applied for solving 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 related to the 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 works [1] to [4] are 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 the equation of state of an ideal gas cannot be applied. In [5] the data reduction method was extended for solving 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 an application to fictive data set will be presented.

2 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 $\alpha(y)$, velocity vector oriented to normal of abscissa |0T| and velocity absolute value $v(y)$) of flowing steam distributed 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 $v(y)$ is solved on the assumption that total specific enthalpy $h_0(y) = h_0$ = given constant.

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

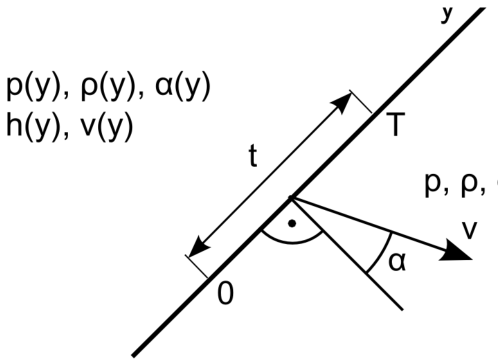

Figure 1: Parameters for two-dimensional steam flow.

The principle of the data reduction method is to solve conservation equations of mass, momentum, and energy. Consequently integrals of mass flux I_M, 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 calculate 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: $$h_{IAPWS-IF97} = f_h(p, \rho) \tag{8}$$

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

$$h - const = \frac{\kappa}{\kappa - 1}\frac{p}{\rho} \tag{9}$$

and is modified into non dimensional form. Reduced parameters can then be solved analytically [3]. The symbol κ is the ratio of heat capacities. For steam flows the system of equations, Eq. (4) to Eq. (8), can be solved using iterative numerical procedure.
In the first iterative step, the value of specific enthalpy *h* is chosen. Then the pressure *p*(*h*) and density *ρ*(*h*) are solved from following equations derived from conservation equations.

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

$$\rho(h) = \frac{I_M}{\sqrt{2(h_0 - h) - \left(\frac{I_C}{I_M}\right)^2}} \tag{11}$$

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

$$h_{IAPWS-IF97}(h) = f_h(p(h), \rho(h)) \tag{12}$$

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

$$h_{IAPWS-IF97} = h \tag{13}$$

Iterative procedure proved to be fast. A graphical aid can help to find solutions of the system of conservative equations supplemented with equation of state of steam. The points of intersection in diagram with curves of $h = f(p)$ and $h_{IAPWS-IF97} = f(p)$ dependencies 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 the thermodynamic and flow parameters is performed by means of IAPWS-IF97 functions and system of equations from data reduction method:

Density	$\rho = f_\rho(p, h)$	(14)
Velocity	$v = \sqrt{(I_A - p)^2 + I_C^2} / I_M$	(15)
Flow angle	$\alpha = \arcsin\left(I_C / (I_M v)\right)$	(16)
Temperature	$T = f_T(p, h)$	(17)
Specific entropy	$s = f_s(p, h)$	(18)
Speed of sound	$a = f_a(p, T)$	(19)
Total pressure	$p_0 = f_p(s, h_0)$	(20)
Total temperature	$T_0 = f_T(p_0, h_0)$	(21)
Dryness of steam	$x = f_x(p, h)$	(22)

3 Application of Data Reduction Method for Two-Dimensional Flow Fields of Steam

Two sets of data were prepared as a task for verification of the data reduction method in steam flow field. The data were prepared manually to simulate 100 measuring points.
First dataset was split into two variants so for the calculation there were different input data groups chosen. First part was composed from y-coordinate, $p(y)$, $\rho(y)$, $v(y)$, $\alpha(y)$ assuming given velocity $v(y)$ and unknown H_0 and $h_0(y)$ so the $h_0(y)$ was calculated according to the Eq. (7) and then total enthalpy H_0 was calculated using the following integral

$$I_E = \frac{1}{t}\int_0^t h_0(y)\rho(y)v(y)\cos\alpha(y)dy \tag{23}$$

and consequently the total value of enthalpy H_0 equals to:

$$H_0 = \frac{I_E}{I_M} \tag{24}$$

The second variant was composed from y-coordinate, $p(y)$, $\rho(y)$, $h_0(y)$ = const., $\alpha(y)$ assuming given $h_0(y)$ = const. = 3000 kJ/kg and the velocity $v(y)$ was calculated using Eq. (7). The aim was to check whether the two resulting solutions will be the same independently of the chosen values for calculation from the same dataset.
The second set was representing slightly different data, again given by y-coordinate, $p(y)$, $\rho(y)$, $v(y)$, $\alpha(y)$ and the calculation was the same as for the first variant of the first data set – for given velocity $v(y)$ and unknown H_0, $h_0(y)$ the total value was calculated by $H_0=I_E/I_M$. For details see the Tab. 1.
On the following graphs, there are simulated data plotted in the h-s diagram (thermodynamic properties) and the hodograph (v_x-v_y velocity components). Both solutions of the data reduction system are depicted in graphs (in h-s diagrams, there are static values for both solutions plotted).

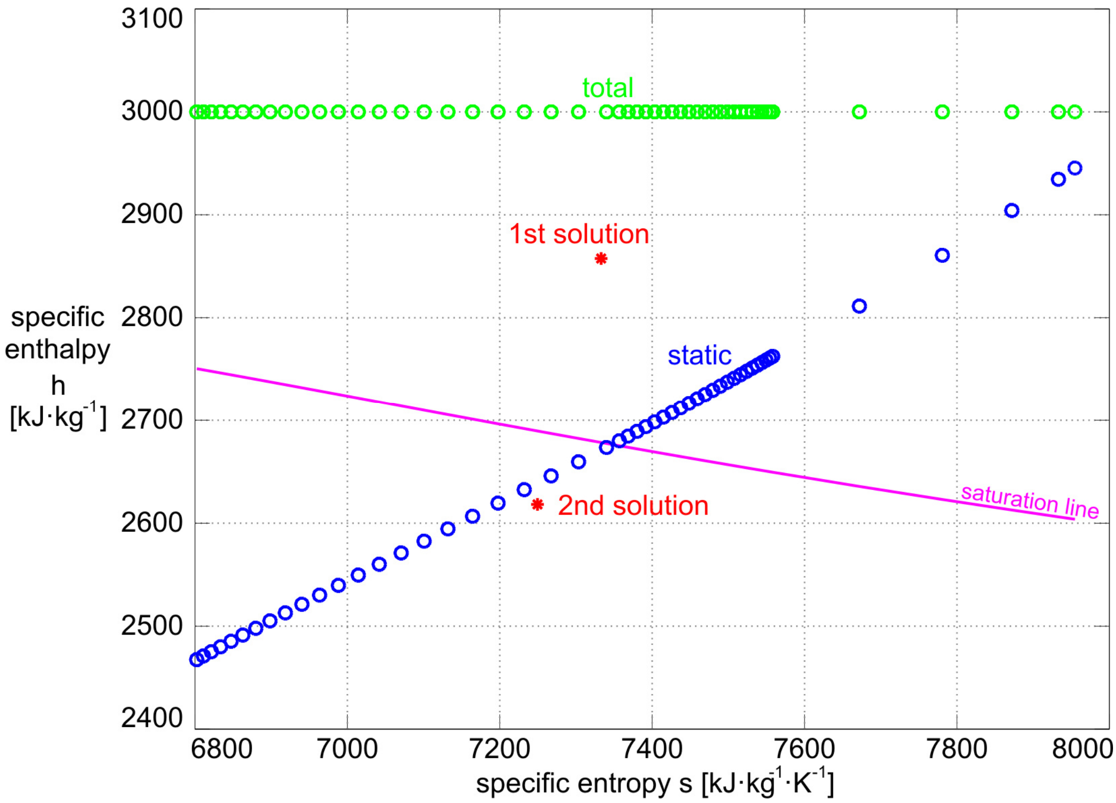

Figure 2: Data points from the first dataset in *h*-*s* diagram.

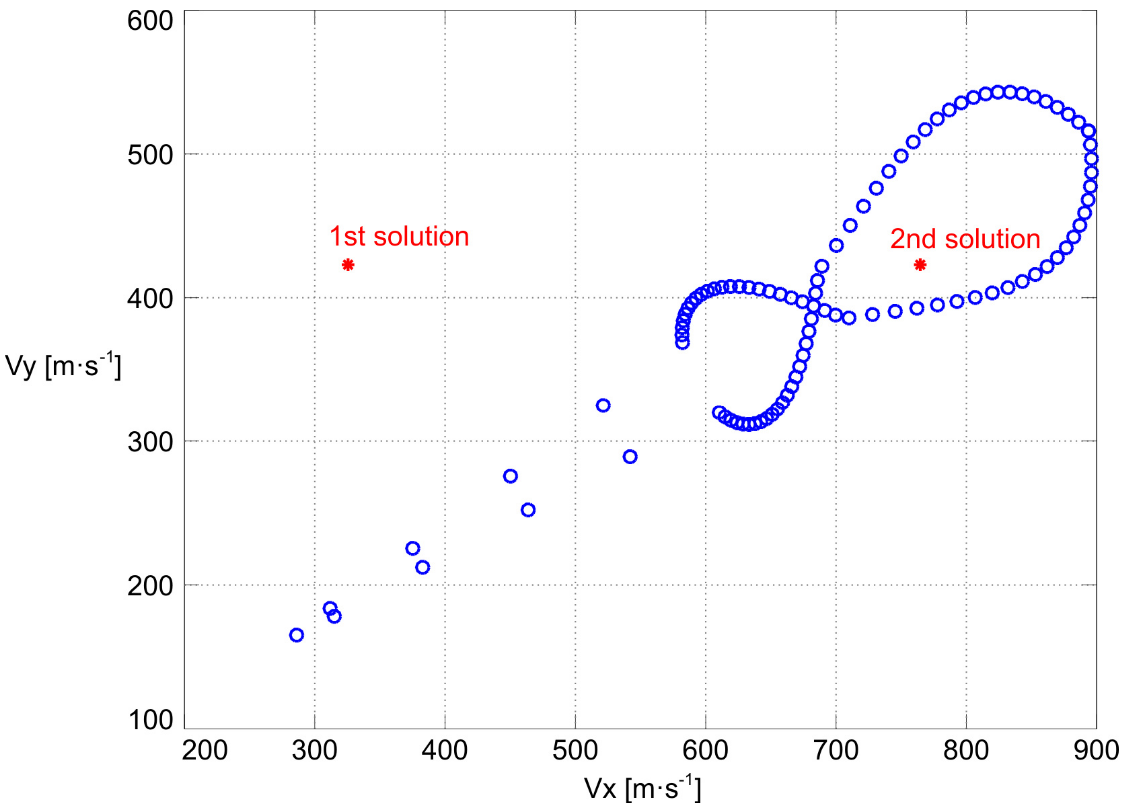

Figure 3: Data points from the first dataset in hodograph (v_x-v_y).

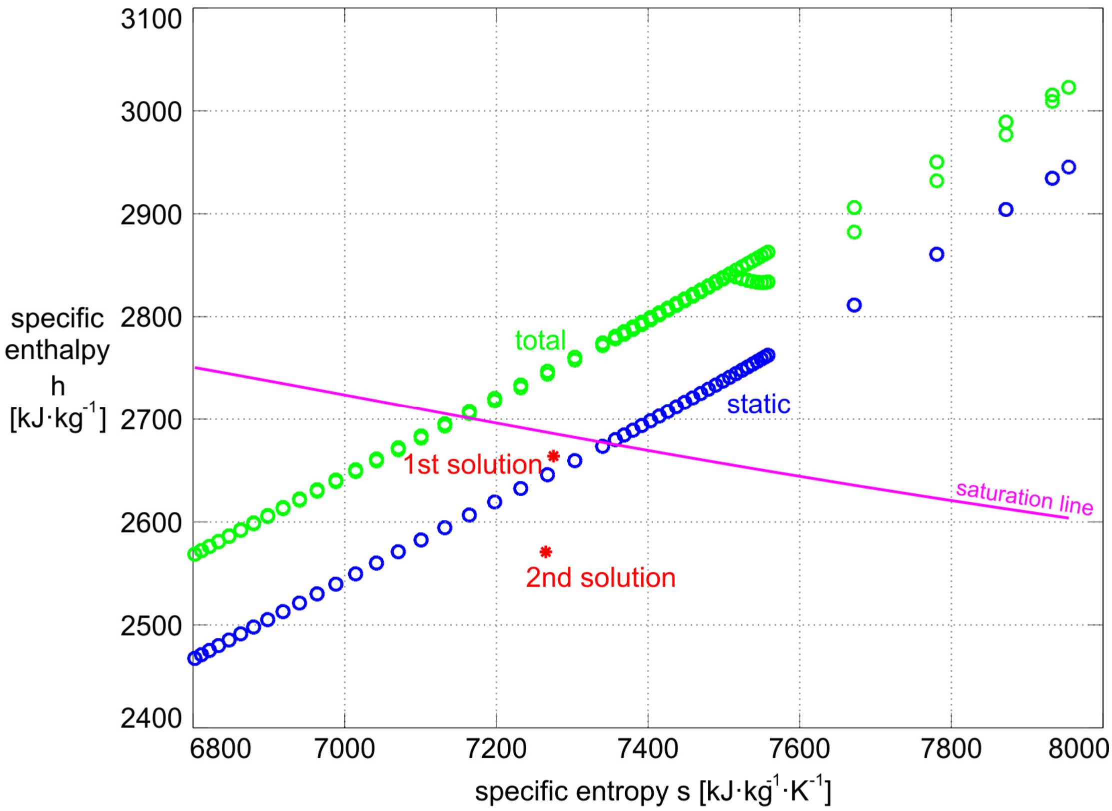

Figure 4: Data points from the second dataset in *h*-*s* diagram.

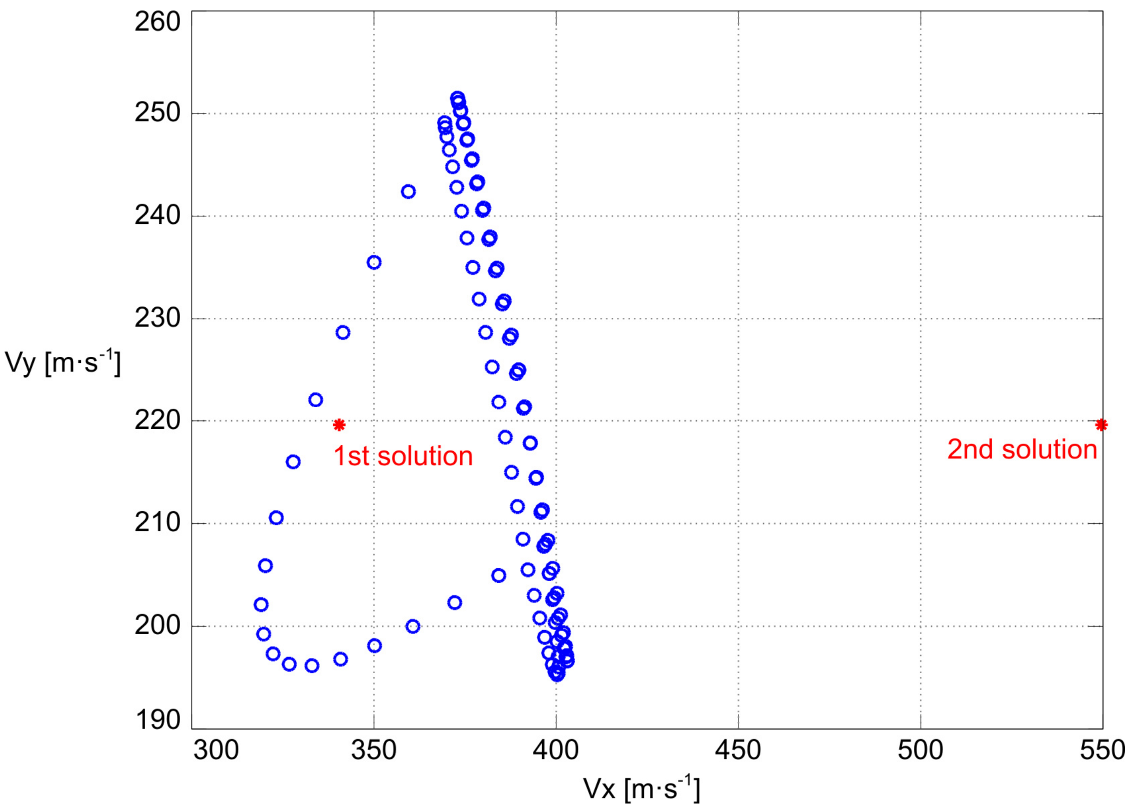

Figure 5: Data points from the first dataset in hodograph (v_x-v_y).

		Dataset 1				Dataset 2	
		*		**		*	
		1^{st} solution	**2^{nd} solution**	1^{st} solution	**2^{nd} solution**	**1^{st} solution**	2^{nd} solution
integrals	I_A	413204		413568		189892	
	I_C	178345		178556		49746	
	I_M	421.908		422.144		226.525	
	I_E	1265531631		1266430915		622063721	
H_0 [J.kg^{-1}]		2999546		3000000		2746111	
p_2 [Pa]		275830.00	**90793.00**	276140.00	**90792.00**	**112760.00**	65392.00
h_2 [J.kg^{-1}]		2857200.00	**2618200.00**	2857600.00	**2618200.00**	**2664000.00**	2571000.00
ρ_2 [m^3.kg^{-1}]		1.2958	**0.5521**	1.2967	**0.5521**	**0.6653**	0.4122
s_2 [J.kg^{-1}.K^{-1}]		7332.80	**7249.50**	7333.00	**7249.50**	**7275.30**	7265.20
v_2 [m.s^{-1}]		533.58	**873.30**	533.75	**873.81**	**405.16**	591.86
α_2 [rad]		0.91444	**0.50527**	0.91482	**0.50529**	**0.57283**	0.38013
*		given velocity $v(y)$ and unknown H_0, $h_0(y)$ the total value was calculated by $H_0=I_E/I_M$					
**		given $h_0(y)$ = const. = 3000 kJ.kg^{-1} and velocity $v(y)$ was calculated					

Table 1: Results of the data reduction method.

4 Results and Discussion

Results from the first dataset were for both variants (as described in Sec. 3) identical as expected, proving, that the method is independent on the input data chosen from the data set. For both cases there was necessary to decide, which solution is the proper one. For judging this there was a major help using the hodograph visualizing the velocity components to see, where the solution is placed by means of the velocity and angle (or velocity components, that is equivalent). The *h*-*s* diagram may not be sufficient for reliably identifying the proper solution.

5 Conclusions

The data reduction method is extended for solving 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 testing 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 was identified.

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.
In the region of transonic and supersonic velocities, the system of conservation equations has two solutions. Identification of the correct solution should be studied in more detail to be able to develop robust mechanism to identify the proper solution. 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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