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MODIFIED DIAGRAM FOR STEAM-WATER INJECTOR MIXING CHAMBER

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ABSTRACT

The scope of this paper is a thermodynamic process in mixing chamber of supersonic steam-water injector. This injector is actually a simple heat pump due to the fact that it can substitute a pump and heat exchanger. Initial energy source of supersonic steam-water injector is usually a small amount of steam with low thermal properties which could not be used for more demanding utilities.

The aim of wider investigation is to build up a relatively high pressure of hot water at the outlet of mixing chamber during a "forced condensation" of steam which is in the cold water surrounding in mixing chamber. Forced condensation, which is described by modified Mollier diagram of wet steam, reveals clearer picture of this complex flow process.

The paper emphasizes Mach number ($M=v/c$) which, largely, represents flow process in mixing chamber. Sound velocity (c) is a physical property of fluid which is a function of different parameters (T, ρ, η, pipeline elasticity, solid impurities, gas bubbles). Intensity of sound velocity, in the case of steam-water injector, depends mostly on steam wetness. Experiments showed that flow process without shocks is possible and worthwhile because it provides the increase of efficiency rate and reliable operation. In addition, it can be concluded that the flow is without interruption and shocks due to small velocities of sound and fluid, which refers to outlet of mixing chamber where M=1. Momentum equation provides a possibility to determine location and intensity of average pressure (p_{ave}) in mixing chamber.

Accepted principles for description and analyses of thermodynamic processes in mixing chamber are based on process continuity, homogeneous flow field and thermodynamic and compressible flow laws. Experimental investigation was done in Laboratory for Fluid Mechanics, at the Faculty of Technical Sciences in Novi Sad, Serbia.

KEYWORDS

Steam-water injector, mixing chamber, forced condensation, modified Mollier diagram, supersonic mixing chamber

1. INTRODUCTION

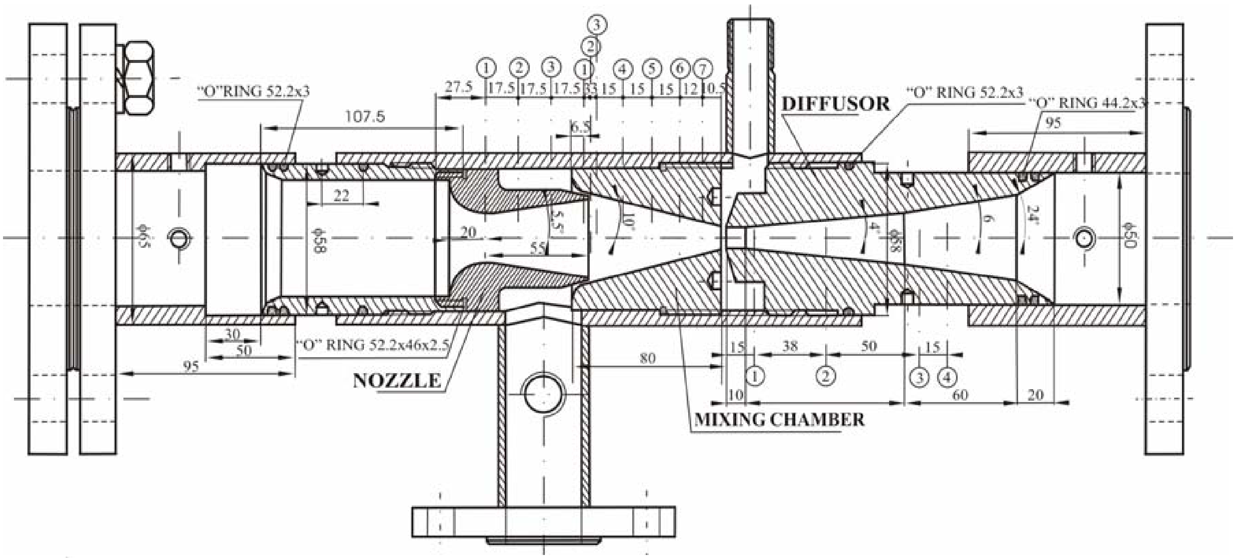
A possibility to gain pressure and rise temperature of mixture of cold water and steam was registered more than 120 years ago. Injector was instantaneously applied in feeding steam boiler with water. However, until today, reasonable and acceptable explanation of what really happens in mixing chamber has not appeared, although there have been numerous attempts. Many registered patents for different purposes of steam-water injector pointed out the usefulness of this device. Hence, striving to explain thermodynamic flow process through mixing chamber is fully justified. Detailed research of *Deich and Filipov* (1968) provided real basics for further investigations.

Steam and water parameters in experiments are: ratio steam-cold water is 1:5; p_s=2.5 bar; t_s=127.5 °C; t_{cw}=10-30 °C; t_{hw}=65-85 °C. In Fig. 1. is presented experimental steam-water injector. Pressure rise in mixture of steam and water, which is an intensive process of forced condensation, obey laws of compressible (supersonic) flow. Supersonic flow of steam at the outlet of Laval's nozzle, due to its dominating volume, transfers into the region of steam-water mixture. Locally formed shock waves, different in origin, are negligible when injector works properly. Conducted experimental research proved a possibility to maintain shock-less flow along injector. Relevant questions, which deserve precise answers, are:

- Which part of pressure rise in mixing chamber can or cannot be connected directly to enthalpy of initial steam?
- How to define sources and nature of losses in mixing chamber and determine efficiency rate of mixing chamber and total injector.

Mentioned shock-less transition of steam through Laval's nozzle and mixture through outlet throat of mixing chamber, can be explained with diagram of isentropic flow in supersonic regime (Fig.

2). This diagram is valid, to a certain extent, for homogenous mixture flow with considerable participation of steam in volume (Tab. 1, row 6.5).



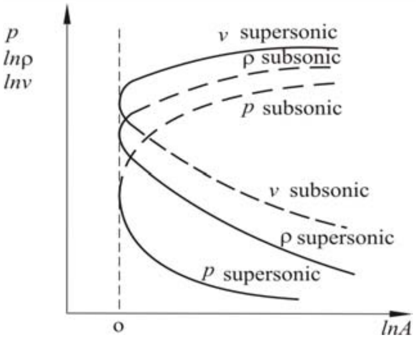


Fig. 1. Configuration of measuring locations and different possitions of Laval's nozzle and mixing chambers (Bukurov 2004)

Gradients of compressible properties of mixture (p, ρ) are specially large in very wet mixture at outlet section of mixing chamber, where transition from supersonic to subsonic flow takes place.

Fig. 2. Isentropic changes of flow parameters through supersonic-subsonic transition as function of nozzle geometry

2. MODIFIED ENERGY DIAGRAM

Modified diagram or diagram of forced condensation allows comparing three types of condensation processes:

- natural - free condensation of steam – without flow under p=const., T=const. (Mollier diagram)
- free condensation - flow without direct mixing of steam and water under $p\neq$const. and $T\neq$const. (Mollier diagram)
- forced condensation with direct mixing of steam and water ($\mathrm{grad}p_{forced} > \mathrm{grad}p_{free}$).

Range of condensation in modified diagram corresponds to borders of mixing chamber where the whole condensation process takes place. Energy change, no matter if condensation is free or forced, is from 2500 kJ/kg to 0 kJ/kg (Fig. 3).

Graphical presentation of processes during forced condensation in mixing chamber, due to introduced cold water, provides better physical view than applicable analytic equations. Also, there are open possibilities to make conclusions about certain parts of processes as well as data which can help to organize experiments more efficiently.

Diagram p-h is the most convenient way to present the results of investigation.

Forced condensation begins when water is introduced into steam region. It has four basic characteristics:

- Condensation process is faster and lasts shorter;
- Geometry of mixing chamber is changed (central angle of conical mixing chamber increases);
- Gradients of physical, flow and energy characteristics, which are functions of time and distance, are considerably larger;
- Temperature through condensation process is below steam temperature at the inlet of Laval's nozzle (127.5 °C, Fig.3).

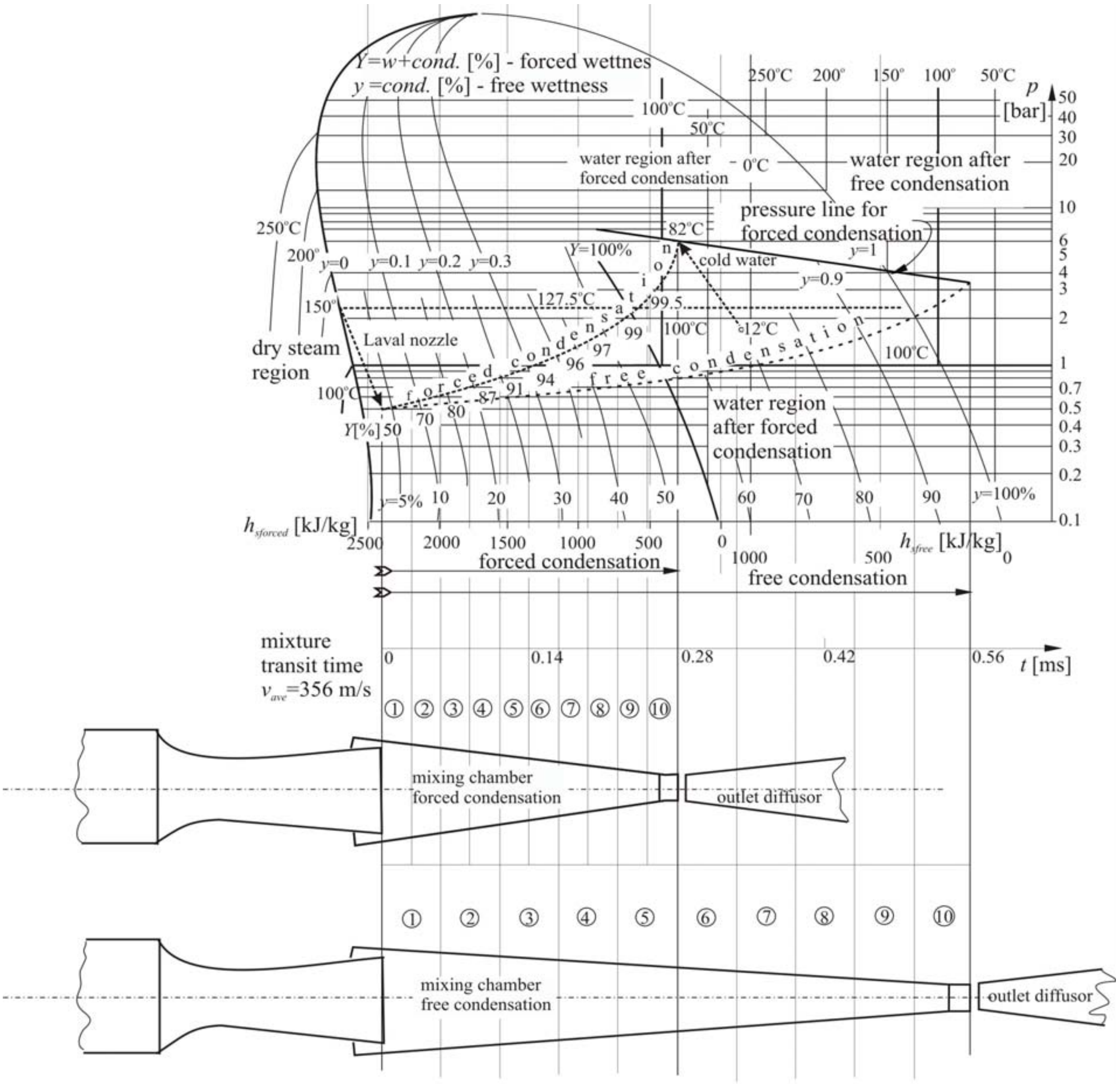


Fig. 3. Energy and geometry change in mixing chamber for forced and free condensation

3. LOCAL CONDENSATION PARAMETERS *X*, *Y*

Modified energy diagram is formed by drawing new lines (*X*, *Y*) in Mollier diagram (*x*, *y*) of wet steam. Steam quality *X* is a concentration of dry saturated steam (*x*=*X*). Wetness *Y* is water fraction which is involved during forced condensation. In Mollier diagram of wet steam, *x* and *y* represent mass fractions of dry saturated steam and water under standard (static) conditions. It is possible to reach such conditions during the flow (hypothetically) when every section of mixing chamber is instantaneously separated. Masses of steam and water are calculated for each section (1-10 in Fig.3). This type of concentration of steam and water is called local concentration, i.e. local dryness (steam quality) and wetness.

Although total amount of cold water is introduced at the entrance of mixing chamber, it is considered that cold water is mixing with wet steam along the whole mixing chamber. Mixing occurs in such manner that each 1/10 of inlet water is mixed with steam in every section and thus, mixture (*X*, *Y*) is produced. Unmixed part of water flows further. Hence, there are two different kinds of water: water for mixing (*wm*) and the rest of water (w*rest*).

Condensation of steam (*y*) is conducted continuously and homogenously along the whole mixing chamber. Definition of free condensation (*p*=const., *T*=const.) is valid for forced condensation too, although pressure and temperature rise. Volume of steam in mixing chamber corresponds to uniform condensation profile in the mixing nozzle according to *Beithou et al.* (2000).

Mass characteristics of steam and water, i.e. dryness X and wetness Y along the mixing chamber are determined according to velocities of steam (υ_s) and water flow through chamber, which are presented in Table 1. Velocity diagram (υ_s,υ_m) is presented according to experimental results and flow laws.

Table 1. Characteristic values of mixture in sections of mixing chamber

Inlet properties of steam and water: $\dot{m}_s = 0.17$ kg/s; $\dot{m}_w = 0.85$ kg/s. Assumption: steam condenses equally in each section of mixing chamber; cold water mixes with steam evenly in each section of mixing chamber; the rest of cold water, which does not mix, stays inert.

No. of section i		1	2	3	4	5	6	7	8	9	10
Geometry of sections											
1.1	d_{iave} [cm]	3.28	3.04	2.8	2.56	2.32	2.08	1.84	1.6	1.36	1.12
1.2	A_i [cm^2]	8.44	7.25	6.15	5.14	4.22	3.4	2.66	2.01	1.45	0.98
1.3	V_i [cm^3]	8.44	7.25	6.15	5.14	4.22	3.4	2.66	2.01	1.45	0.98
Characteristics of steam											
2.1	υ_s [m/s]	710	680	650	600	530	450	350	250	150	50
2.2	ρ_s [kg/m^3]	0.338	0.395	0.45	0.507	0.646	1.0	1.40	1.7	2.16	3.0
2.3	$\dot{m}_s$ [kg/s]	0.161	0.144	0.127	0.110	0.093	0.08	0.059	0.04	0.02	0.008
2.4	Q_s [l/s]	478	366	283	218	145	76.5	39.2	25	11.2	0.28
2.5	A_s [cm^2]	6.729	5.628	4.358	3.632	2.73	1.7	1.122	1.0	0.79	0.566
Characteristics of condensate in the central part of each section (0.05, 0.15,...0.95)											
3.1	$\dot{m}_{con}$ [kg/s]	0.0085	0.025	0.0425	0.0595	0.0765	0.093	0.11	0.127	0.144	0.15
3.2	Q_{con} [l/s]	0.0085	0.025	0.0425	0.0595	0.0765	0.093	0.11	0.127	0.144	0.15
3.3	A_{con} [cm^2]	0.0001	0.0004	0.0006	0.001	0.0014	0.002	0.0031	0.005	0.009	0.03
Characteristics of water for mixing $\upsilon_{wm}=0.5\upsilon_s$											
4.1	υ_{wm} [m/s]	355	340	325	300	265	225	175	125	75	25
4.2	Q_{wm} [l/s]	0.085	0.17	0.255	0.34	0.425	0.51	0.595	0.68	0.765	0.85
4.3	A_{wm} [cm^2]	0.0024	0.005	0.0078	0.011	0.016	0.023	0.034	0.054	0.102	0.34
Characteristics of rest of water											
5.1	$\dot{m}_{wrest}$ [kg/s]	0.765	0.68	0.595	0.51	0.425	0.34	0.255	0.17	0.085	0
5.2	A_{wrest} [cm^2]	1.708	1.617	1.783	1.496	1.473	1.675	1.501	0.946	0.55	0.044
5.3	υ_{wrest} [m/s]	4.479	4.205	3.337	3.409	2.885	2.030	1.699	2.24	1.797	0
Volumes of fluids											
6.1	V_s [cm^3]	6.729	5.628	4.358	3.632	2.73	1.7	1.122	1.0	0.788	0.566
6.2	V_{wm+con} [cm^3]	0.0025	0.0054	0.0084	0.012	0.0174	0.025	0.0371	0.059	0.112	0.37
6.3	$V_{s+wm+con}$ [cm^3]	6.7315	5.6334	4.3664	3.644	2.7474	1.725	1.159	1.059	0.9	0.936
6.4	V_{wrest} [cm^3]	1.708	1.617	1.783	1.496	1.473	1.675	1.501	0.946	0.55	0.044
6.5	V_s/V_{wm+con} [-]	2691.6	1042.2	518.8	302.7	157	68	30.2	16.9	7	1.53
6.6	$V_s/(V_{s+wm+con}+V_{wrest})$ [-]	0.8	0.776	0.708	0.706	0.647	0.4	0.421	0.5	0.543	0.604
Masses of fluids											
7.1	m_s [g]	0.0022	0.0022	0.0019	0.0018	0.0018	0.0017	0.0016	0.0017	0.0017	0.0003
7.2	m_{wm+con} [g]	0.0025	0.0054	0.0084	0.012	0.0174	0.025	0.0371	0.059	0.1112	0.37
7.3	m_{wrest} [g]	1.708	1.617	1.783	1.496	1.473	1.675	1.501	0.946	0.55	0.044
7.4	m_{wtotal} [g]	1.71	1.622	1.791	1.508	1.49	1.7	1.538	1.005	0.662	0.414
Mixture humidity during forced condensation $Y=(m_{wm+con})/(m_s+m_{wm+con})$ $X=m_s/(m_s+m_{wm+con})$											
8.1	Y [-]	0.527	0.707	0.812	0.867	0.908	0.936	0.959	0.972	0.985	0.999
8.2	X [-]	0.473	0.293	0.188	0.133	0.092	0.064	0.041	0.028	0.015	0.0007
Exponent of polytrophic process (Deich, 1968)											
9.1	κ [-]	1.08	1.015	0.95	0.86	0.76	0.67	0.5	0.38	0.25	0.01

where are in Tab 1.

2.5 $A_s = \dfrac{\dot{m}_s}{\rho_s v_s}$; 3.1 $\dot{m}_{con} = \dot{m}_{sin} - \dot{m}_s = 0,17 - \dot{m}_s$; 3.3 $A_{con} = \dfrac{(0.05....0.95)\dot{m}_s}{\rho_w v_{con}}$, $v_{con} = v_s$;

4.3 $A_{wm} = \dfrac{Q_{wm}}{v_{wm}}$, ; 5.1 $A_{wrest} = A_d - (A_s + A_{con} + A_{wm})$; 5.1 $\dot{m}_{wrest} = \dot{m}_w - \dot{m}_{wm}$;

5.2 $A_{wrest} = A_i - (A_s + A_{con} + A_{wm})$; 5.3 $v_{wrest} = \dfrac{\dot{m}_{wrest}}{\rho_w A_{wrest}}$

Mass flow rates of steam and water are determined with their entrance values ($\left(\dot{m}_s\right)_{in}$ =0.17 kg/s, $\dot{m}_{cw}$ =0.85 kg/s). It is assumed that mixing and condensation are consistent in each section of the chamber. Volume flow rates of steam are determined according to data given in steam table for density (ρ) as function of pressure and temperature. Density of steam through chamber is changeable from 0.338 to 3.0 kg/m^3.

Velocity of water through mixing chamber, as well as its volume in considered section (i=1,2,...10), are determined according to geometry of mixing chamber and volume of steam.

Characteristics of water-steam mixture in certain sections of mixing chamber are shown in Table 1. Steam is condensed (*con*) in each section of mixing chamber equally. Cold water (*cw*) is mixed with steam equally in each section of mixing chamber, too. The rest of cold water (*rest*) which is not mixed with steam jet does not participate in steam water mixture formation. Entrance and exit diameters of experimental chamber are 3.4 and 1 cm. Length of chamber is 10 cm, and each section is 1 cm long. Volume of chamber is 41.70 cm^3.

4. BASICS FOR ENERGY FLOW ANALYSES

Borders of polytrophic flow

Relation between volume of steam (V_s) and volume with active water (V_{con}+V_{wm}) is authoritative for estimation to which length of mixing chamber laws of gas dynamics are valid. It could be seen that steam is still present even in the last section of the chamber.

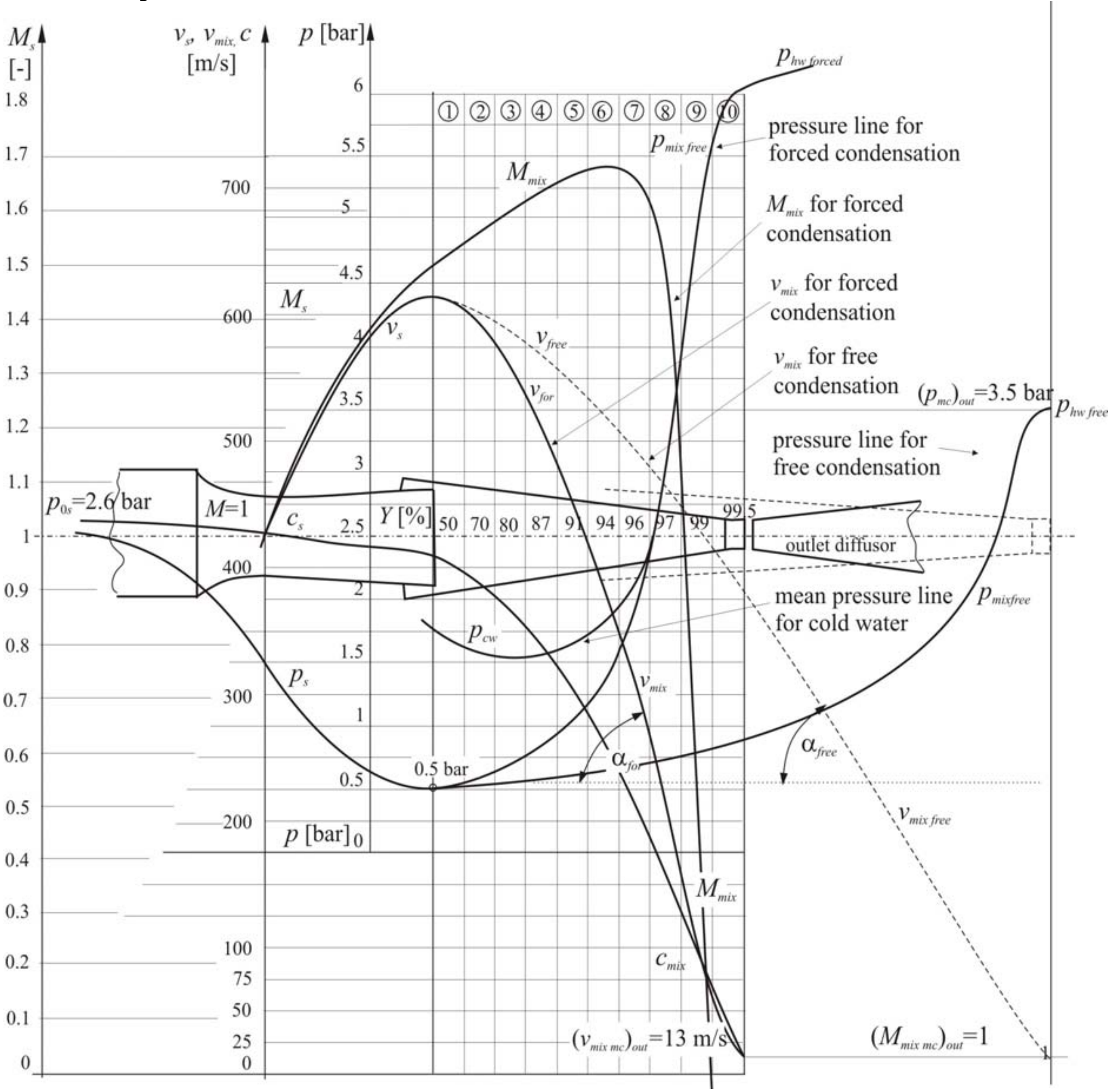


Fig 4. M, v, p comparative diagram for forced and free condensation

High wetness of steam water mixture through the whole mixing chamber causes low sound velocities and high Mach numbers, which confirms the behavior of compressible flow together with the given polytrophic exponents κ (*Deich and Filipov* 1968).

The basic task is to determine a volume of steam and water along the mixing chamber. Steam carries total energy and thus, steam flow laws can be estimated according to thermodynamic relations with certain corrections. The flow is conducted in certain volume, so relation V_s/V_w determines the area of mixing chamber in which these relations are valid. It is considered that this border is within 2/3 of mixing chamber length which is agreeable with *Narabayashi et al.* (2000).

Basic relations

Basics for analyses of complex energy flow process through mixing chamber are given in:

- diagram of isentropic changes of flow parameters through supersonic-subsonic transition (Fig 2.)
- change of sound velocity (c) and polytropic exponent (κ) depending on relevant factors of influence (*Deich and Filipov* 1968)
- basic equations (Eq. 1 to 3) for the flow of compressible flow

$$\frac{v^2}{2}+\frac{c^2}{\kappa-1}=const. \tag{1}$$

$$\frac{p_t}{p}=1+\frac{\kappa}{2}M^2+\frac{\kappa}{8}M^4+\ldots \tag{2}$$

$$\frac{T_t}{T}=1+\frac{\kappa-1}{2}M^2 \tag{3}$$

- energy equation (Eq. 4)

$$\left[\left(h_s+\frac{v_s^2}{2}+\frac{p_s}{\rho_s}\right)\dot{m}_s\right]_{\substack{in\\mc}}+\left[\left(h_{cw}+\frac{v_{cw}^2}{2}+\frac{p_{cw}}{\rho_{cw}}\right)\dot{m}_{cw}\right]_{\substack{in\\mc}}=\left[\left(h_m+\frac{v_m^2}{2}+\frac{p_m}{\rho_m}\right)\dot{m}_{hw}\right]_{\substack{out\\mc}}+h_l\dot{m}_{hw}. \tag{4}$$

Momentum equation

Momentum equation, as it is known, is without any practical limitation in application on any flow process. It is applied on control volume which represents mixing chamber and takes into account only changes on borders of control volume. Its simplicity and reliability leads to accurate information which, in this case, gives magnitude of average pressure in mixing chamber.

Control volume (Fig. 5) represents two inlet sections (steam and cold water) and one outlet – throat of mixing chamber. It is well known that this law governs only those parameters which prevail on borders of control volume. Inner changes are negligible. This simple relation determines average pressure in mixing chamber. According to *Bukurov* (2004), it is possible to determine more accurate pressure distribution in mixing chamber with known average pressure p_{ave}.

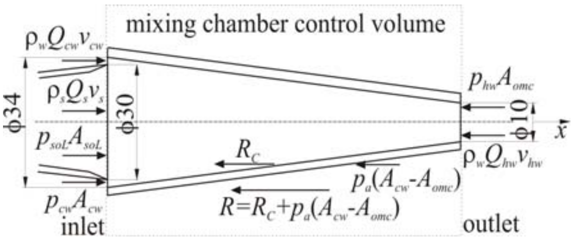


Fig. 5 Momentum equation applied to mixing chamber

If average pressure in mixing chamber increases, pressure at the throat of mixing chamber also increases.

The influence of surrounding to insulated mixing chamber is realized with forces which are presented in Fig. 5. Momentum equation is given as

$$F_{ps}+F_{pcw}-F_{phw}-F_a+F_{cw}+F_s-F_{hw}-R_c=0 \tag{5}$$

From here, the pure reaction of connection is

$$R_c=F_{ps}+F_{pcw}-F_{phw}-F_a+F_{cw}+F_s-F_{hw} \tag{6}$$

On the other hand, pure reaction R_c can be presented with average pressure in mixing chamber acting on orthogonal projection of mixing chamber:

$$R_c=p_{mave}\left(\left(A_{mc}\right)_{in}-\left(A_{mc}\right)_{out}\right) \tag{7}$$

where is p_{mave} – is average manometric pressure in mixing chamber. Combination of eq. (6) and (7) leads to average manometric pressure

$$p_{mave}=\frac{F_{ps}+F_{pcw}+F_{cw}+F_s-(F_{phw}+F_a+F_{hw})}{\left(A_{mc}\right)_{in}-\left(A_{mc}\right)_{out}} \tag{8}$$

Forces that act on mixing chamber are (v_{cw}=4.1 m/s; v_{hw}=13 m/s):

$$F_{ps} = p_{soL}A_{soL} = 50000\times 0.03^2\times\pi/4 = 35.34\ \mathrm{N} \tag{9}$$

$$F_{pcw} = p_{cw}A_{cw} = 180000\times\left(0.034^2 - 0.03^2\right)\pi/4 = 36.19\ \mathrm{N} \tag{10}$$

$$F_{phw} = p_{hw}\left(A_{mc}\right)_{out} = 600000\times 0.01^2\pi/4 = 47.12\ \mathrm{N} \tag{11}$$

$$F_s = \rho_s Q_s v_s = \dot{m}_s v_s = 0.17\times 611 = 103.87\ \mathrm{N} \tag{12}$$

$$F_{cw} = \rho_w Q_{cw} v_{cw} = \dot{m}_{cw} v_{cw} = 0.85\times 4.1 = 3.48\ \mathrm{N} \tag{13}$$

$$F_{hw} = \rho_w Q_{hw} v_{hw} = \dot{m}_{hw} v_{hw} = 1.02\times 13 = 13.26\ \mathrm{N} \tag{14}$$

$$F_a = p_a\left((A_{mc})_{in} - (A_{mc})_{out}\right) = 101325\cdot(0.034^2 - 0.01^2)\cdot\frac{\pi}{4} = 84.04\ \ \mathrm{N}\,. \tag{15}$$

All pressures in equations above are absolute.

By substituting eq. (9)-(15) into eq. (8), p_{mave} is determined:

$$p_{mave} = \frac{35.34 + 36.19 + 3.48 + 103.87 - (47.12 + 84.04 + 13.26)}{\dfrac{\left(0.034^2 - 0.01^2\right)\pi}{4}} = 41670\ \ \mathrm{Pa}\,. \tag{16}$$

Average pressure p_{mave} rises if known terms in numerator of eq. (8) are greater. Forces acting at the outlet of mixing chamber are considered as given. Average pressure depends to the greatest extent on F_s, since relations of forces are following: F_s/F_{ps}=3, F_s/F_{pcw}=3, F_s/F_{cw}=35. These values are known from experimental investigations. If it is possible to provide higher pressure of cold water at the entrance of mixing chamber, without extra energy, efficiency rate of mixing chamber increases proportionally. But, if cold water is on atmospheric pressure, or even lower, vacuum at the entrance of mixing chamber will suck in cold water what is a valuable technical advantage (pupm for cold water is not necessary); and efficiency rate decreases compared to previous case. Force F_{cw} is neglectable. Force F_s is three times greater than force F_{ps}, and from energy point of view, it is more favourable to achieve higher steam velocity at the outlet of Laval nozzle, which requires decrease of pressure p_s at the outlet of Laval nozzle. The limit to which it is possible to decrease outlet steam pressure from Laval nozzle p_{sL} depends on possibility to maintain isentropic steam expansion without schocks. Higher steam pressure at inlet of Laval nozzle provides higher values of F_{ps} and F_s, what should be used if steam of such quality is at disposal.

For experimentaly gained inlet and outlet values D_{oL}=30 mm, $(D_{mc})_{in}$ =34 mm, $(D_{mc})_{out}$ =10 mm, $\dot{m}_s = 0.17$ kg/s, $\dot{m}_m = 1.02$ kg/s, p_{cw}=1.8 bar, p_{os}=2.6 bar, p_{hw}=6 bar, v_{cw}=4,1 m/s, v_{hw}=13 m/s, average absolute pressure in mixing chamber is 1.42 bar.

5. CONCLUSION

Inaccessible and deficient data on what happens in mixing chamber during the flow of supersonic mixture of cold water and steam is one of the reasons for conducting a careful investigation on this complex process of forced condensation. Unstable flow conditions through injector over a longer period of time hinders accurate measuring and its reviewing. Determining relatively accurate pressure change through mixing chamber would lead to more precise analyses of established procedures and conditions in mixing chamber.

Since the general laws are non-existent, analyses of complex energy transformation through injector device demand puzzle like collection of data and filling in reliable details.

Reliable details presented in this paper are:

- Mach number strongly represents the process. Sound velocity c entirely depends on mixture wetness, and thus, analytic relations of compressible flow can be applied. Dynamic relation of compressible flow consists of inertial and elastic forces (v^2, κM^2) and can be applied to flow process in mixing chamber, taking into account change of κ.
- Modified diagram of forced condensation locates energy and flow changes in corresponding cross sections in mixing chamber. Diagram connects energy surrounding (superheated steam and cold water) with flow process, which can be directed into desired course. Diagram of forced condensation indicates that in order to get higher pressures of warm water, shorter condensation process with higher wetness seems to be more appropriate.
- Determining magnitude of average mixture pressure in mixing chamber (p_{ave}) enables to get a more accurate pressure distribution in mixing chamber and geometry of mixing chamber, according to the inlet parameters. Application of momentum equation provides a clear inside of forces acting in mixing chamber. The influence of some of these forces to pressure change in the

chamber is obvious and thus, there is no need for further investigation. Considerably high deceleration of mixture velocity in front of the mixing chamber throat, during forced condensation, in comparison with free condensation (tgα in Fig. 3), is a measure of outlet pressure increase. Outlet pressure multiplied by cross section area is acting inertial force.

Further investigation predicts:

- Determining velocity distribution in mixing chamber by using LDA of new generation and its comparison with the research of *Dumaz et. al.* (2005).
- Investigating central water nozzle and annular steam nozzle and its comparison with the research of *Deberne et. al.* (1999). That investigation could deal with determination of friction losses on the wall with annular introduction of steam in mixing chamber.

NOMENCLATURE

A	[cm^2]	cross section area
h	[J/kg]	enthalpy
$\dot{m}$	[kg/s]	mass flow rate
p	[Pa]	pressure
Q	[m^3/s]	flow rate
q	[J/kg]	heat energy
T	[K]	temperature
t	[°C]	temperature
V	[m^3]	volume
v	[m/s]	velocity
X	[%]	dryness during forced condensation
x	[%]	dryness during free condensation
Y	[%]	wetness during forced condensation
y	[%]	wetness during free condensation
ρ	[kg/m^3]	density

Subscripts

0	total
a	atmosferic
ave	average
con	condensed
cw	cold water
d	diffuser
hw	hot water
i	section number (i=1,2,...10)
in	inlet
L	Laval's nozzle
l	losses
m	manometric
mc	mixing chamber
mix	mixture
out	outlet
s	steam
w	water
wm	water for mixing
wrest	the rest of water

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