THEORETICAL ADVANTAGES OF HOT GAS ATOMIZATION OF MELTS

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INTRODUCTION

The atomization of metal melts is a highly effective method to produce metal powders. The process has achieved great market success due to its very high productivity and flexibility. There are many attempts to develop an equation to describe gas atomization. Most of them are only empirical relationships between the particle size and a number of dimensionless groups. [1,2] These are not universal and cannot be applied to every case. The authors try to build a theoretical background of atomization to explain particularly the positive effect of the use of pre-heated gas, which has been observed by several authors. [3,4, 5,6]
The theory should include description of gas jet energy. One of the authors has tried to make such view. [7] But this study was limited by taking into consideration only parameters for 1 kg of the gaseous media. In practice it is very rare to have a variable area gas nozzle to keep mass flow rate constant. It is more normal to fix the nozzle profile and change initial gas parameters to influence the atomization process. In the paper we try to analyse the characteristics of gas jets for the case of fixed nozzle area.

THE EFFECT OF GAS PARAMETERS ON SUPERSONIC STREAM CHARACTERISTICS.

In his latest monograph [2] Dr. Ternovoy has surveyed the studies devoted to mechanism of molten metal atomization. According to him there are six stages of melt jet disintegration by a gas stream:
Transformation of the initial metal jet into conical film;
Development of the waves of instabilities parallel and orthogonal to the metal jet velocity vector;
Formation of a toroidal thickening of the liquid at the end of the film;
Development of instability in the toroidal thickening;
Formation of micro jets of the melt flowing from the area of maximum instability of the film;
Development of unstable waves within micro jets and their disintegration into droplets.
This treatment of the physical model allows the author to establish the equation:

$$d_k = (2.91\, \nu_m^{0.4}\, \rho_m^{0.2}\, D_j^{0.63})/(\sigma_m^{0.026}\, \rho_g^{0.17} w_g^{0.34}) * \{(gh + \Delta P/\rho_m)/(gh + 2\Delta P/\rho_m)\}^{0.086}$$

Where;
d_k – diameter of the droplet;
ν_m – kinematic viscosity of the melt;
ρ_m – metal density;

D_j – diameter of metal jet;
σ_m – surface tension of the melt;
ρ_g – gas density;
w_g – gas velocity;
g – gravitation acceleration;
h – height between metal level and focal point of atomization;
ΔP – pressure difference between metal level and metal nozzle outlet.

In this equation the gas density and velocity are the most important parameters. But there is no gas to metal flow ratio at all**.** To include gas to metal flow ratio is more normal for empirical equations. Here instead the metal flow rate is involved through diameter of metal jet, height between metal level and focal point of atomization and pressure difference between metal level and metal nozzle outlet. We also note a very small dependence on surface tension. Gas density and velocity present the effect of its parameters. So it could be concluded that gas density and velocity are the most important. But these are not sufficient to describe the atomization process.

To atomise the liquid melt the gas jet should have enough kinetic energy (power), dynamic pressure and quantity of momentum or jet force. All of these include gas flow rate.

Gases are compressible and continuous. Our analysis assumes only ideal fluids. The main characteristic of gaseous media is variable density (kg/m^3) which depends on Temperature and Pressure. So it is better to measure gas flow rate in kg/s then in normal m^3/s.
Our terms regarding fluids are:

G – mass flow rate, kg/second
ρ – density, kg/m^3
T – temperature, Kelvin
P – pressure, MPa absolute value
w – velocity, m/s
R – gas constant is Universal Gas Constant 8314 J/(mol K=Degree of Kelvin) divided on mol of specific gas
v – specific volume, m^3/kg – the reciprocal of the density
a_0 – velocity of sound at standard condition (P=0.1 MPa, T=273K)
a_{loc} – local velocity of sound (P=current, T=current)
A – area of the nozzle, m^2
M – Mach number is ratio of the actual jet velocity to the local sonic velocity
λ – velocity coefficient; the ratio of actual velocity to local critical velocity (velocity at the narrowest cross-section at the current critical pressure and temperature)
k – adiabatic coefficient. k = 1.66 – for monoatomic gases (He, Ag), 1.40 – for diatomic (air, N_2) 1.31 for CO_2, 1.33 – for steam
C_v C_P - heat capacity (J/(molK) at constant volume and constant pressure correspondingly ($k=C_p/C_v$)
i – gas enthalpy, J/mol

sqrt(..) – means square root (All basic gas equations here and further are quoted from [8], all gas thermodynamic parameters are taken from [9])

From the theory of gas dynamics it is known there is limitation of the maximum achievable gas jet velocity.
This is given by:
$i_1 - i_2 = 0.5(w_2^2 - w_1^2)$ (1)
Increasing the velocity depends on only the difference between initial and final gas enthalpy.
If the initial $w_1=0$ and the initial enthalpy is used entirely for acceleration ($i_2=0$) we have

$w_{max}=sqrt(2i_1)$ (2)

$i_1=C_p*T_1$ (3)
hence

$$w_{max}=sqrt(2\ C_p*T_1) \qquad (4)$$

Thus for any initial gas temperature there is the only one maximum velocity of its jet. And it is clear that the higher the initial temperature of the gas the higher the velocity that can be achieved.

To accelerate a gas jet a Laval-type nozzle is applied.
A typical Laval nozzle profile is given in Fig. 1

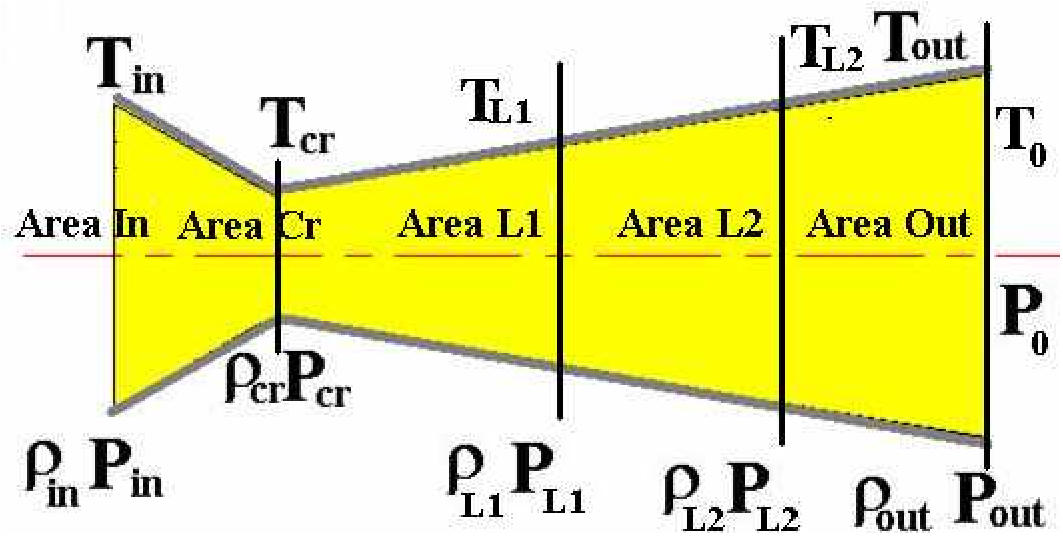

Fig. 1. Typical Laval nozzle profile

As a rule a Laval nozzle outlet cross-section is calculated assuming $P_{out} = P_0$

As the fluid medium is continuous it is known that its mass flow rate is constant:

$$G=Const \text{ and } G= Aw\rho \text{ (Area x Velocity x Density) kg/s} \qquad (5)$$

Mach number is very often used to describe the behaviour of a gas stream passing through the nozzle.

$$(M^2 - 1) * \partial w/w = \partial A/A \qquad (6)$$

By using the Mach number and differential equation (6) we can characterize the behaviour of the gas flowing along the nozzle.

If $M < 1$ (subsonic case) and Area reduces then Pressure falls and Velocity rises. This is the case of the jet acceleration of the stream till sonic velocity.

If $M > 1$ (super sonic case) and Area increases then Pressure falls and Velocity rises. This is the case for the acceleration of the stream above sonic velocity - acceleration of the stream up to $P_{out} = P_0$ (Pressure of environment media)

If $M=1$ it is the case of critical velocity of the jet. Velocity of the jet is equal to the local sonic velocity which depends on only initial gas parameters.

Velocity coefficient λ is very often used to calculate the nozzle profile because it simplifies the equation.

Gas flows through the nozzle adiabatically (i.e. without heat exchange with its surroundings). The gas parameters can thus be calculated using adiabatic process equations.

They are here:

$$P/\rho^k = Const \qquad (7)$$

$$P_{out}/P_{in} = (\rho_{out}/\rho_{in})^k \qquad (8)$$

$$T_{out}/T_{in} = (\rho_{out}/\rho_{in})^{(k-1)} \qquad (9)$$

$$T_{out}/T_{in} = (P_{out}/P_{in})^{(k-1)/k} \qquad (10)$$

Let consider the atomisation process from point of gas circulation as working media in whole. Such scheme is given in Fig. 2.

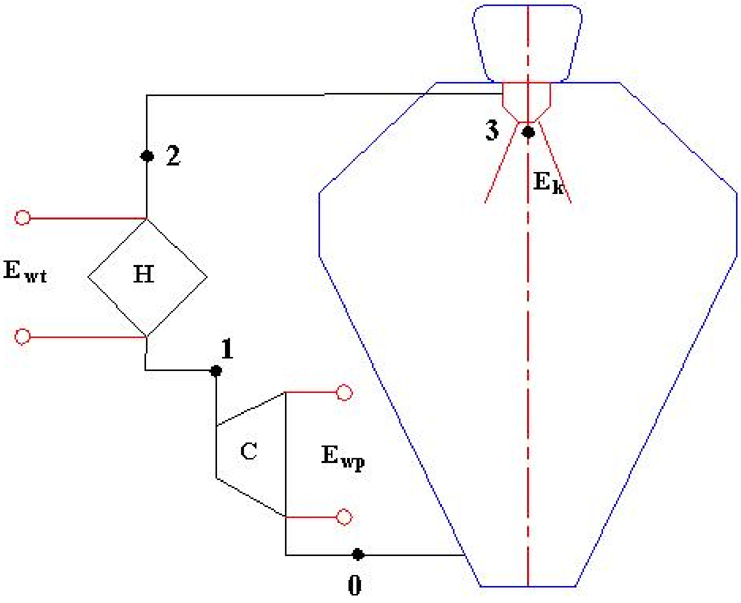

Fig. 2. Schematic gas circulation in the atomisation process

Here are C – compressor, H – gas heater, E_{wt} – energy applied to preheat the gas, E_{wp} – energy applied to compress the gas. Initial point of the process is marked here **0.** Parameters of gas are P_0 and T_0. The compressor **C** compresses the gas up to P_1 and T_1 (Point **1**) One needs to apply energy $\mathbf{E_{wp}}$ here. Then gas comes to heater **H** where it is preheated up to T_2 at P_2 (Point **2)**. Applied energy is $\mathbf{E_{wt}}$. The gas expands flowing through the Laval nozzle and releases energy $\mathbf{E_k}$ – kinetic energy of the gas jet (Point **3**).

After interaction with metal jet, droplets and environment the gas returns to point **0.**

According the scheme of the Laval nozzle (Fig 1) $P_1=P_2=P_{in}$, $T_0=T_1$, $T_2=T_{in}$, $P_{out}=P_0$, $T_{out}\neq T_0$

Thus there are following processes:-

- Points 0-1 apply compressing energy:

$E_{wp} = [(P_0/\rho_0)*k/(k-1)]*[(P_{in}/P_0)^{(k-1)/k}-1]$, {J/kg} – specific energy per kg (11)

-Points 1 – 2 apply preheating energy:

$E_{wt}=C_p(T_{in}-T_0)$, {J/kg} – specific energy per kg (12)

(Full energy in {W} is multiplied with gas flow rate G_g in {kg/s}

- Points 2-3 release kinetic energy:

$E_k=0.5w_{out}^2G_g$, {W} – full kinetic energy of gas jet (13)

-Points 3-0 – interaction with metal jet and recycling process of the gas.

The main characteristic of any process is its effectiveness. It is necessary to apply an amount of energy to do any useful work. In our case the applied energy is E_{wp} (energy of work to pressurize the gas) and E_{wt} (energy to elevate its temperature). The useful energy is kinetic energy of the gas jets.

Hence, effectiveness η is:

$\eta= E_k/[G_g*(E_{wp}+E_{wt})]$ (14)

Assume that the initial pressure of the gas P_{in}=Const and only T_{in} is variable hence E_{wp}=Const too.

Using velocity coefficient λ and following equations:

$w_g = \lambda*w_{cr}$ (15)

$w_{cr} = sqrt(kR_gT_{cr})$ (16)

$T_{cr}= T_{in}*[1- \lambda_{cr}^2*\{(k-1)/(k+1)\}]$ (17)

λ_{cr} =1 – by definition

We obtain the following equation for the effectiveness as a function of initial gas temperature and velocity coefficient:

$\eta= [0.5 \lambda^2kR_gT_{in}\{1-(k-1)/(k+1)\}]/[E_{wp}+C_p(T_{in}-T_0)]$ (18)

As for monoatomic gases k=1.66 and for diatomic gases k=1.40 we can make the equation (18) more clear:

Monoatomic $\eta_1=[0.624\ \lambda^2 R_g T_{in}]/[[E_{wp}+C_p(T_{in}-T_0)]$ (19)

Diatomic $\eta_2=[0.583\ \lambda^2 R_g T_{in}]/[[E_{wp}+C_p(T_{in}-T_0)]$ (20)

The equations (19) and (20) show that with T_{in} increasing both numerator and denominator will increase too. So with increasing of temperature of gas preheating the effectiveness of the process should change negligibly. But the opposite is true in the case of higher gas pressures. It is clear that with increasing compressing energy E_{wp} the effectiveness must decrease.

Dynamic pressure is:

$$P_{gj} = 0.5\rho_{out}\ w_{out}^2 \quad (21)$$

With using equations (8-10, 15-17) we can show that dynamic pressure does not depend on initial gas temperature at all. It is finally:

$P_{gj}= 0.624\ \lambda^2 P_{in}*[(P_{out}/P_{in})^{0.602}]$ - for monoatomic gases (22)

$P_{gj}= 0.583\ \lambda^2 P_{in}*[(P_{out}/P_{in})^{0.714}]$ - for diatomic gases (23)

According to our case P_{in}= Const and $P_{out}=P_0$=Const the dynamic pressure of the gas jets will remain constant independent of initial gas temperature. It is clear that dynamic pressure will increase with increasing velocity coefficient and growth of initial pressure of the gas.

The quantity of momentum or jet force is the next gas jet characteristic.
It is :

$$F= G_g\ w_g,\ \{kg/s*\ m/s = N\} \quad (24)$$

This characteristic allows us to calculate average velocity of gas-metal spray.

According to conservation of momentum there is a balance:

$$G_g\ w_g +G_m\ w_m = w_a\ (G_g + G_m) \quad (25)$$

Here w_a means average velocity of gas-metal spray after impaction of the gas jet with metal jet in the focal point of atomisation.

Let $r= G_g/G_m$ (the gas/metal ratio) and after transformation one obtains:

$$w_a =(rw_g +w_m)/(r+1) \quad (26)$$

For the case of the fixed nozzle area, with initial increase of temperature gas flow rate and correspondingly gas to metal (mass)flow ratio will decrease but gas velocity will be rise strongly. Hence, average spray velocity will go up having a positive influence on atomisation.

The examples of calculation illustrate the above conclusions:
Assume the following conditions:

Initial pressure	P_{in}=1 MPa (10 Bar)
Initial temperature	T_{in}=293K (20°C)
Fixed critical area	A_{cr}=6.32 mm^2
Fixed outlet area	A_{out}=10.57 mm^2
Monoatomic gas	Helium
Diatomic gas	Nitrogen
Initial gas to metal flow rate ratio	1
Metal jet velocity	2 m/s

Results of calculation for He are given in table 1.
Results of calculation for N_2 are given in table 2.

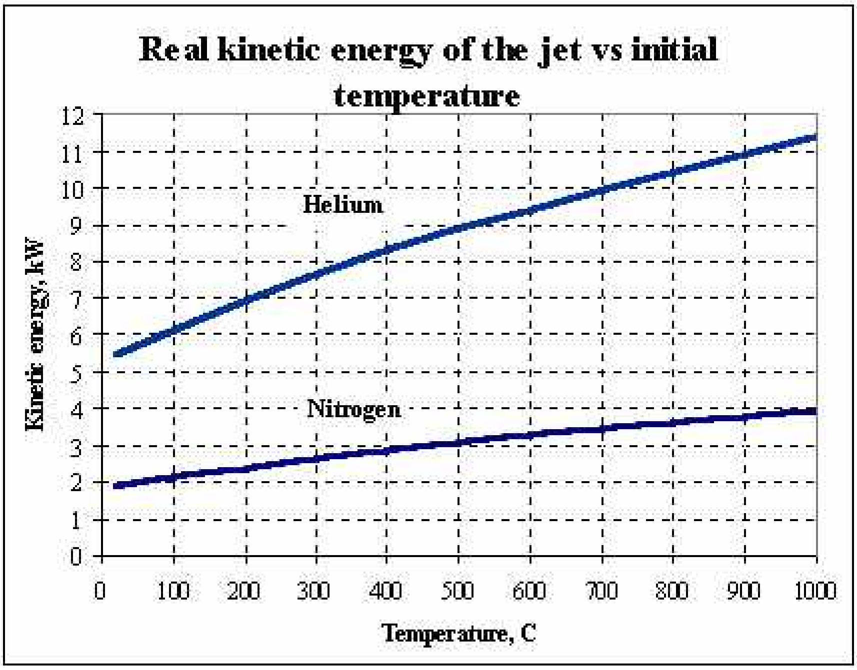

Fig. 3. Real kinetic energy of the gas jet vs initial temperature of the gas

Table 1 Results of calculation for Helium

Data	Var1	Var2	Var3	Var4	Var5	Var6	Var7	VAr8	Var9	Var10	Var11
Initial Pressure, P_{in} Bar	10	10	10	10	10	10	10	10	10	10	10
Initial Temperature, T_{in} C	20	100	200	300	400	500	600	700	800	900	1000
Fixed Critical Area, mm^2	6.32	6.32	6.32	6.32	6.32	6.32	6.32	6.32	6.32	6.32	6.32
Fixed Outlet Area, mm^2	10.57	10.57	10.57	10.57	10.57	10.57	10.57	10.57	10.57	10.57	10.57
Standard Dens, kg/m^3	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179
Initial Density, kg/m^3	1.664	1.307	1.031	0.851	0.724	0.631	0.558	0.501	0.454	0.416	0.383
R of Gas, J/kgK	2079	2079	2079	2079	2079	2079	2079	2079	2079	2079	2079
Energy Compress, E_{wp} kJ/kg	2301	2301	2301	2301	2301	2301	2301	2301	2301	2301	2301
Energy Preheat, E_{wt} kJ/kg	0	415	935	1454	1973	2493	3012	3531	4051	4570	5089
Total applied Energy, kJ/kg	2301	2716	3235	3755	4274	4793	5313	5832	6351	6871	7390
Out Temperature, T_{out} C	-156	-124	-84	-44	-4	36	76	117	157	197	237
Out Density, kg/m^3	0.416	0.326	0.257	0.213	0.181	0.158	0.139	0.125	0.113	0.104	0.096
Out Velocity, w_{out} m/s	1355	1529	1722	1895	2054	2202	2340	2470	2594	2712	2825
Mass Flow Rate, G_g kg/min	0.357	0.317	0.281	0.255	0.236	0.220	0.207	0.196	0.187	0.179	0.171
Kinetic Energy 1 kg, kJ/kg	919	1170	1483	1797	2111	2424	2738	3052	3365	3679	3993
Dynamic Pressure, MPa	0.382	0.382	0.382	0.382	0.382	0.382	0.382	0.382	0.382	0.382	0.382
Kinetic Power at real mass flow rate, kW	5.467	6.169	6.947	7.646	8.286	8.880	9.437	9.963	10.463	10.939	11.396
Effectiveness,%	39.94	43.07	45.85	47.86	49.39	50.58	51.54	52.33	52.99	53.55	54.03
Average velocity of the spray, m/s	679	720	760	791	818	840	859	876	892	905	917

Table 2 Results of calculation for Nitrogen

Data	Var1	Var2	Var3	Var4	Var5	Var6	Var7	VAr8	Var9	Var10	Var11
Initial Pressure, P_{in} Bar	10	10	10	10	10	10	10	10	10	10	10
Initial Temperature, T_{in} C	20	100	200	300	400	500	600	700	800	900	1000
Fixed Critical Area, mm^2	6.32	6.32	6.32	6.32	6.32	6.32	6.32	6.32	6.32	6.32	6.32
Fixed Outlet Area, mm^2	10.57	10.57	10.57	10.57	10.57	10.57	10.57	10.57	10.57	10.57	10.57
Standard Dens, kg/m^3	1.250	1.250	1.250	1.250	1.250	1.250	1.250	1.250	1.250	1.250	1.250
Initial Density, kg/m^3	11.647	9.149	7.214	5.955	5.070	4.415	3.909	3.507	3.180	2.909	2.681
R of Gas, J/kgK	297	297	297	297	297	297	297	297	297	297	297
Energy Compress, E_{wp} kJ/kg	282	282	282	282	282	282	282	282	282	282	282
Energy Preheat, E_{wt} kJ/kg	0	83	186	291	399	508	620	734	850	968	1088
Total applied Energy, kJ/kg	282	364	468	573	680	790	902	1016	1132	1250	1370
Out Temperature, T_{out} C	-121	-80	-28	24	76	127	179	231	283	335	386
Out Density, kg/m^3	2.249	1.766	1.393	1.150	0.979	0.852	0.755	0.677	0.614	0.562	0.518
Out Velocity, w_{out} m/s	542	611	688	758	821	880	935	987	1037	1084	1129
Mass Flow Rate, G_g kg/min	0.773	0.685	0.608	0.553	0.510	0.476	0.448	0.424	0.404	0.386	0.371
Kinetic Energy 1 kg, kJ/kg	147	187	237	287	337	387	437	487	538	588	638
Dynamic Pressure, MPa	0.330	0.394	0.394	0.394	0.394	0.394	0.394	0.394	0.394	0.394	0.394
Kinetic Power at real mass flow rate, kW	1.890	2.133	2.402	2.643	2.865	3.070	3.263	3.445	3.617	3.782	3.940
Effectiveness,%	52.07	51.27	50.61	50.06	49.55	49.03	48.50	47.99	47.49	47.01	46.56
Average velocity of the spray, m/s	272	288	304	317	328	337	344	351	357	363	368

Using data from tables 1 and 2 several plots are built.

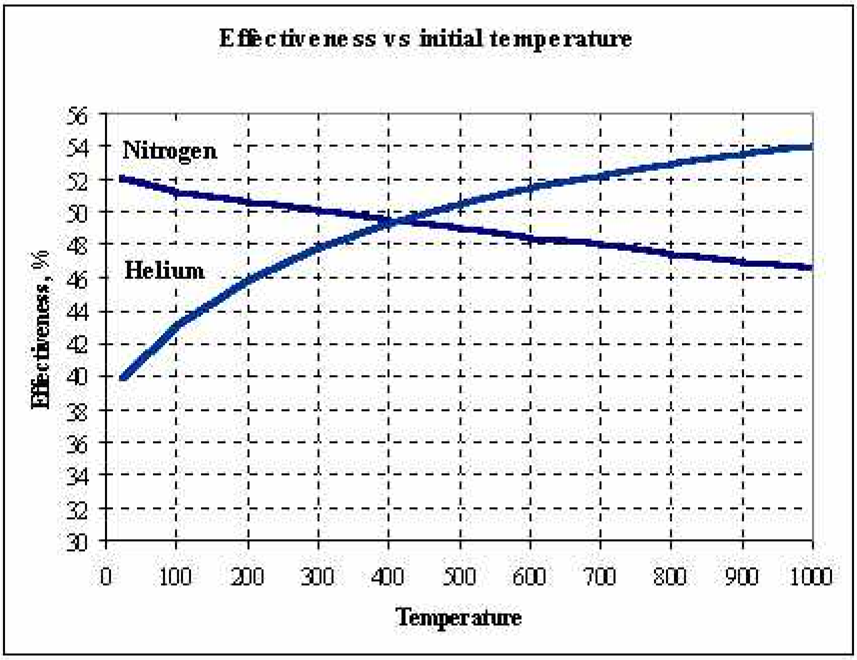

Fig. 4 Effectiveness of applied energy vs initial temperature of the gas

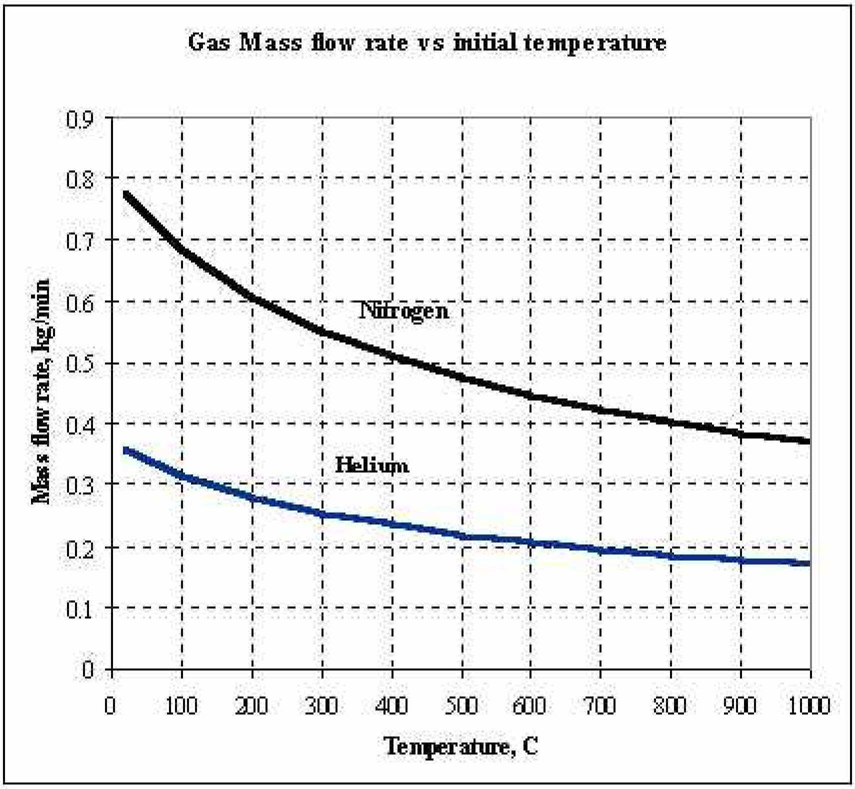

Fig. 5 Real mass flow rate of the gas through nozzle with fixed area vs initial temperature of the gas

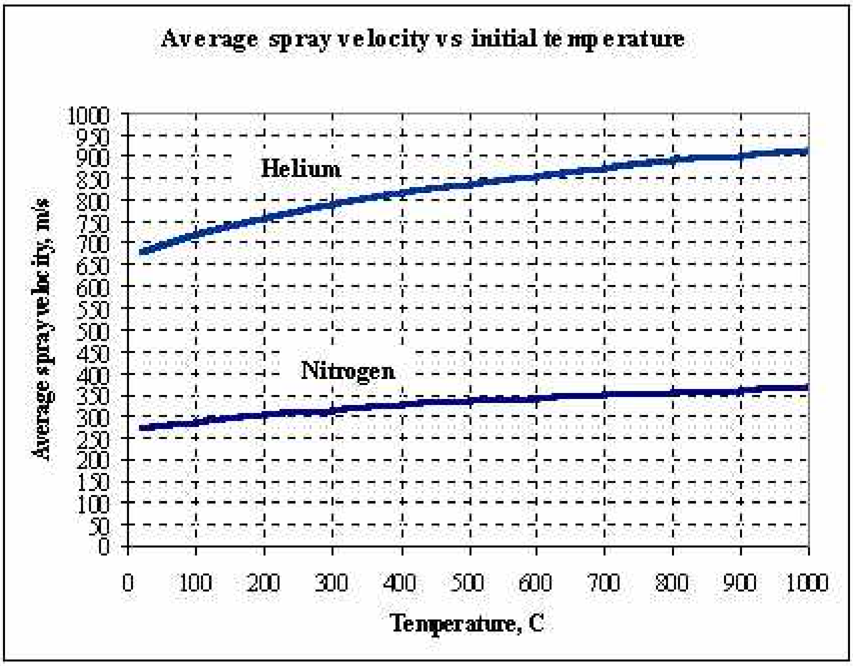

Fig. 6 Average velocity of the spray vs initial temperature of the gas

Thus, with increasing initial gas temperature its jet velocity increases, the effectiveness of the process improves (in case of Helium) or at least remains practically the same, its dynamic pressure remains constant. In the case of fixed nozzle area gas the mass flow rate will decrease reducing gas consumption of the process and at the same time provide better average velocity of the spray.
On basis of the tables 1 and 2 and plots shown in Fig.3-6 the following conclusions are drawn.

CONCLUSIONS

Preheating the gas greatly increases the jet velocity and its kinetic energy.

Despite the decrease of gas density and its mass flow rate through a fixed nozzle, the dynamic pressure of the jet remains constant.

The lighter gas (Helium) provides much higher value of kinetic energy despite the fact that its mass flow rate is half as much through the same fixed nozzle.

The effectiveness of applied energy in the case of the lighter monoatomic gas grows with increasing temperature and slightly reduces in the case of nitrogen.

Gas preheating, despite reducing the gas mass flow rate, increases the average spray velocity.

The lighter gas provides a much higher average spray velocity due to its higher initial jet velocity.

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