CONDENSED GASES JET GENERATOR FOR NANOLITHOGRAPHY

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Introduction

Development of lithographic devices using super rigid ultra-violet radiation (nanolithograph) is carrying out in many microelectronics centers at present. A source of such radiation is laser plasma. The most preferable is plasma activated in condensed noble gases, especially in xenon [1, 2].

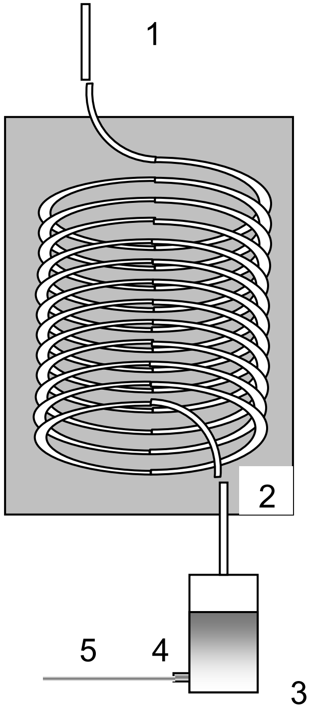
The jet of condensed xenon as a source of ultra-violet radiation possesses some advantages. They are a rich spectrum of radiation in demanded area with the large efficiency of transformation of laser radiation and absence of contamination of a surface of optical details of nanolithograph during its work. However at use of xenon there is also a number of problems. The main things from them are high cost and need of powerful system of evacuation.

Theory and estimations

Calculation of parameters of flow and condensation.

Functionally jet generator consists of 4 basic parts: the pipeline bringing gas, the condenser, the store of liquid xenon and nozzle.

On the pipeline gas is moved to the condenser and preliminary cooled. Walls of the condenser are at constant temperature T_w. In the condenser gas is cooled up to the temperature close to wall temperature and condensed if T_w is below temperature of condensation T_C. In the store the homogeneous field of liquid velocities on input in nozzle is formed. Thereby stability of the outflow in a direction is provided.



The block diagram of the jet generator

1 - the pipeline, 2 - the condenser, 3 - the store of liquefied gas, 4 - nozzle, 5 - jet.

Theory and estimations

Calculation of parameters of flow and condensation.

Temperature of condenser wall T_w is above temperature of condensation T_C.

In one-dimensional approach average values of gas flow parameters are defined by the following equations [3]:

$$\frac{du}{u} = -\frac{\kappa M^2}{1-M^2} \cdot \frac{dF}{\dot{m}u} + \frac{1}{1-M^2} \cdot \frac{dQ}{\dot{m}C_P T},$$

$$\frac{dp}{p} = \frac{\kappa M^2 \cdot \left[1 + (\kappa - 1) \cdot M^2\right]}{1-M^2} \cdot \frac{dF}{\dot{m}u} - \frac{\kappa M^2}{1-M^2} \cdot \frac{dQ}{\dot{m}C_P T},$$

$$\frac{dT}{T} = \frac{\kappa(\kappa-1) \cdot M^4}{1-M^2} \cdot \frac{dF}{\dot{m}u} + \frac{1-\kappa M^2}{1-M^2} \cdot \frac{dQ}{\dot{m}C_P T},$$

$$\rho = \frac{Ap}{RT}.$$

Here ***u*, *p*, *T*, *ρ*** *are velocity, pressure, temperature and density of gas averaged on a pipe cross-section;* ***κ*** *- adiabatic constant,* ***M*** *- Mach number* $\dot{m}$ *- the mass consumption;* ***F*** *- the value considering action of external forces (at us they are forces of friction);* ***Q*** *- intensity of a heat supply,* C_P *- heat capacity at constant pressure,* ***A*** *- nuclear weight,* ***R*** *- universal gas constant. Cross-section of pipelines is considered to constants, and gas is ideal.*

Theory and estimations

Calculation of parameters of flow and condensation.

Temperature of condenser wall T_w is above temperature of condensation T_C.

Forces of friction and intensity heat inflow are defined by equations [3, 4]:

$$\frac{dF}{\dot{m}u} = -\xi \cdot \frac{dx}{4r}$$

$$dQ = \alpha \cdot 2\pi r \cdot (T_W - T) \cdot dx$$

*where **r** is radius of the pipeline, **x** - coordinate along length of the pipeline, **α** and **ξ** are found by formulas:*

for laminar flow $\xi = \dfrac{64}{\mathrm{Re}}$ *for turbulent flow* $\xi = 0.11 \cdot \left(\dfrac{Ke}{2r} + \dfrac{68}{\mathrm{Re}} \right)^{0.25}$

$\alpha = Nu \cdot \dfrac{\lambda}{2r},$ $Nu = 3.66$ $\alpha = Nu \cdot \dfrac{\lambda}{2r},$ $Nu = 0.023 \cdot \mathrm{Re}^{0.8} \cdot \mathrm{Pr}^{0.33}$

Reynolds's and Prandtl numbers: $\mathrm{Re} = \dfrac{2\rho u r}{\mu},$ $\mathrm{Pr} = \dfrac{Cp \cdot \mu}{\lambda}$

***λ** - factor of heat conductivity, **Ke** - the equivalent roughness of an wall internal surface of a pipe, **μ** - dynamic viscosity.*

The solution of system was developed by selection of gas velocity on input of the pipeline so that on output from nozzle pressure of gas p_k *was equally critical values (*p_{00} *is pressure of braking)*

$$p_K = p_{00} \cdot \left(\frac{2}{\kappa + 1} \right)^{\frac{\kappa}{\kappa - 1}}$$

After run of calculation on all parts the conditions $p = p_k$ *and* $M = 1$ *were checked. If conditions were not carried out, value of initial gas velosity was corrected. Calculations proceeded until these conditions were satisfied.*

Theory and estimations

Calculation of parameters of flow and condensation.

Temperature of condenser wall T_w is below temperature of condensation T_C.

Parameters of a liquid and gas are defined by other equations [3, 5]:

$$\frac{du}{u} = -u^2 \cdot \left(\frac{1}{RT} - \frac{1}{L}\right) \cdot \frac{dF}{\dot m_g u} + \left(1 - \frac{S_L}{S_g} \cdot \frac{\dot m_g}{\dot m_L} \cdot B\right) \cdot \frac{dQ}{\dot m_g L},$$

$$\frac{dT}{T} = \frac{u^2}{L} \cdot \frac{dF}{\dot m_g u} - \frac{u^2}{L} \cdot \left(2 - \frac{S_L}{S_g} \cdot \frac{\dot m_g}{\dot m_L} \cdot B\right) \cdot \frac{dQ}{\dot m_g L},$$

$$p = p_K,$$

$$\rho = \frac{Ap}{RT},$$

$$\frac{d\dot m_g}{\dot m_g} = -\frac{u^2}{L} \cdot \frac{C_p T}{L} \cdot \frac{dF}{\dot m_g u} + \frac{dQ}{\dot m_g L},$$

$$\frac{dS_g}{S_g} = -\frac{u^2}{L} \cdot \frac{C_p T}{L} \cdot \frac{dF}{\dot m_g u} + \frac{S_L}{S_g} \cdot \frac{\dot m_g}{\dot m_L} \cdot B \cdot \frac{dQ}{\dot m_g L},$$

$$d\dot m_L = -d\dot m_g, \qquad dS_L = -dS_g,$$

$$\frac{\dot m_L}{\rho_L} = u_L \cdot S_L = i \cdot \frac{g r^4}{64\nu} \cdot \frac{(\varphi - \sin\varphi)^3}{\varphi^2}.$$

Here parameters of gas have a previous designation, the mass consumption is the sum of consumptions of gas and liquid, $\dot m = \dot m_g + \dot m_L$ *; the area of pipeline cross-section is also the sum of cross-section areas of gas and liquid* $S = S_g + S_L$ *;* ***L*** *- heat of vaporization. Further, it is assumed that the liquid moves only by gravity inside condenser. Then in last formula* ***i*** *is an incline,* ***g*** *- acceleration of gravity,* ***ν*** *- kinematic viscosity of a liquid and* ***φ*** *- angle of opening of a liquid flat surface in pipe with round cross-section. Values* ***dQ*** *and* $dF / \dot m_g u$ *are defined by previously expressions, but for* ***dQ*** *instead of perimeter* ***2πr*** *it is necessary to substitute*

$$2r \cdot \left(\pi - \frac{\varphi}{2} + \sin\frac{\varphi}{2}\right)$$

That takes into account reduction of cross-section area of the channel for gas at condensation.

Theory and estimations

Calculation of parameters of flow and condensation.

Temperature of condenser wall T_w is below temperature of condensation T_C.

At the solution of system initial parameters were found in the assumption that at excess of pressure over value of condensation pressure the liquation of gas portion occurs in spurts with conservation of weight and energy

$$\dot{m} = \dot{m}_g + m_L\,, \qquad \dot{m} \cdot \left(\frac{u_1^{\,2}}{2} + h_1\right) = \dot{m}_L \cdot h_{L2} + \dot{m}_g \cdot \left(\frac{u_2^{\,2}}{2} + h_2\right)$$

Here ***h*** *is enthalpy, and indexes of* ***1*** *and* ***2*** *concern to a condition before and after jump.*

Theory and estimations

Results of parameters calculation of flow and condensation

Temperature of condenser wall T_w is above condensation temperature T_C *(without condensation)*

Results of calculations of gas flow parameters without condensation (pressure, velocity and temperature of gas, and also its density, Mach number and the mass consumption)

Number part	p (Dyne/cm²)	u (cm/s)	T (K)	ρ (g/cm³)	M	($\dot{m}$
Begin. value	10^6	88	300	0,0016	0,0027	0,00071
End of part 1	999696	25,6	87,2	0,0052	0,0015	0,00071
Begin of part 2	999696	25,6	87,2	0,0052	0,0014	0,00071
End of part 2	999693	23,6	80,5	0,006	0,0014	0,00071
Begin of part 3	999693	1,026	80,5	0,006	0,00006	0,00071
End of part 3	999693	1,026	80,5	0,006	0,00006	0,00071
Enter from nozzle	461728	14382	59	0,0049	0,89	0,00071

It is visible that the Mach number is close to 1 on enter of nozzle, and the mass consumption is constant. It is the confirmation of calculations correctness.

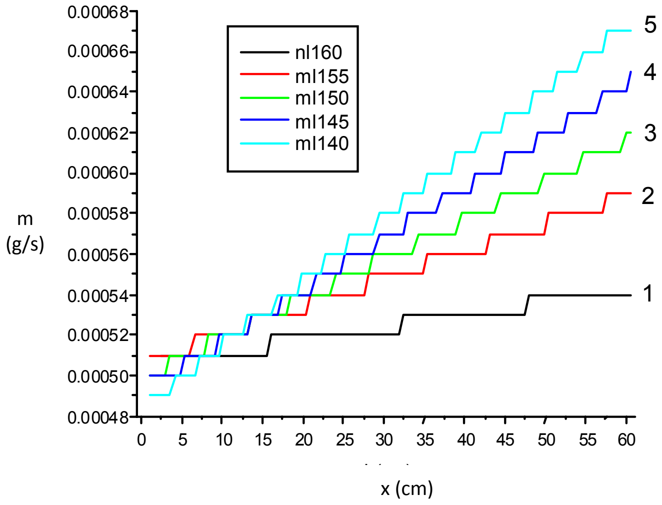
Theory and estimations

Results of parameters calculation of flow and condensation

Temperature of condenser wall T_w is <u>below</u> condensation temperature T_C *(with condensation)*

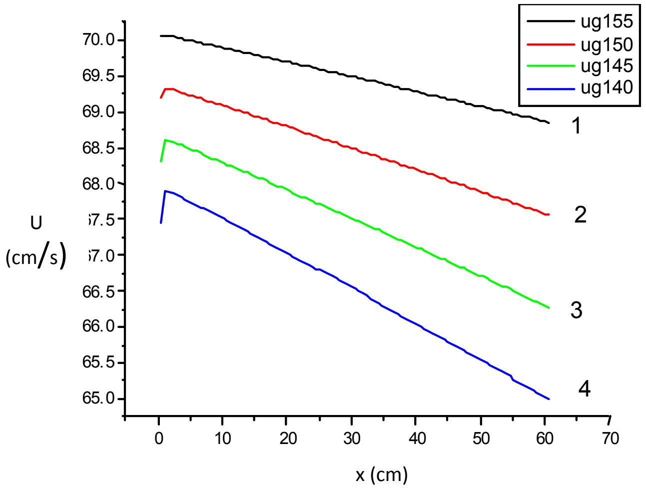
Dependences of the liquid consumption and gas velocity on distance in the condenser.

liquid consumption



The curves 1, 2, 3, 4, 5 correspond to temperature of condenser wall of 160, 155, 150, 145 and 140K.

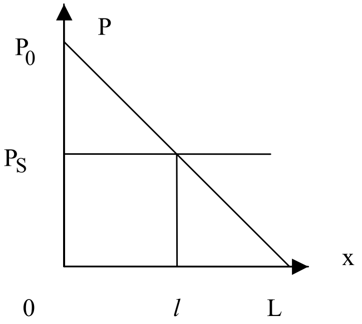
gas velocity



The curves 1, 2, 3, 4 correspond to temperature of condenser wall of 155, 150, 145 and 140K.

Theory and estimations

Problem of a liquid boiling in jet at pressure reduction



At liquid movement in the cylindrical channel with constant section the pressure changes practically linearly from initial pressure upon an input $\boldsymbol{p_0}$ *up to final pressure upon an output* $\boldsymbol{p} \sim 0$*. At any position liquid becomes overheat. As result there are conditions for fast growth of bubbles on impurity particles, and the liquid boils in all volume.*

The condition of that the liquid did not boil at $\boldsymbol{p} = 0$ *could write in the form*

$$r < \frac{2\sigma}{p_S} \quad \text{or} \quad \frac{n_d}{n_{Xe}} < \frac{16\sigma}{p_S\sqrt{Dt}}$$

Here $\boldsymbol{\sigma}$ *is factor of surface tension,* $\boldsymbol{p_S}$ *- saturated vapor pressure,* **D** *- factor of molecule diffusion of an impurity in liquid, and* $\boldsymbol{n_d/n_{Xe}}$ *– relative atomic concentration of impurity.*

For working nozzle unit temperature of 170 K and time from the Xe condensation beginning of 10 min. the estimation gives the maximal maintenance of impurity 0.4 atomic %.

Therefore, to provide the outflow of a jet without spraying it is necessary:

- *to work with well cleared gas;*
- *at possible to lower temperature;*
- *at the large velocity of the outflow of a liquid;*
- *at probably smaller length of a nozzle capillary.*

Problem of jet stability

Development of instability of a jet direction is connected with turbulence. That can be initiated by large bubbles at liquid boiling up and solid microparticles under the high liquid velocity. For short capillaries jet instability arises mainly because of the solid microparticles which have adhered to wall of nozzle.

Theory and estimations

Behavior of a jet in vacuum

*At an output of jet in vacuum the intensive evaporation of liquid begins with a lateral surface as pressure in the vacuum chamber is much less than pressure of saturated vapor at working temperature. Process described by the equation of energy balance in cylindrical jet with radius **a**:*

$$\frac{a\rho C_V}{2}\cdot\frac{dT}{dt} = -LG + Q_R + Q_T + Q_S$$

*Here **ρ** is density of a liquid, $\mathbf{C_V}$ - heat capacity, **T** - average on radius temperature, **L** - heat of evaporation, ε and σ_B are blackness factor of jet and Stephen-Boltzmann constant, **α** - factor of accommodation at collision of gas molecules with a jet, $\boldsymbol{\gamma = C_P/C_V}$, $\mathbf{T_C}$ - temperature of chamber walls, **p** - pressure of gas in the chamber, $\mathbf{L_S}$ is heat of fusion, **dr/dt** – velocity of solidification border.*

$$G = (p_S - \frac{\sigma}{a} - p)\cdot\sqrt{\frac{M}{2\pi RT}}$$

- loss of heat due to evaporation

$$Q_R = \varepsilon\sigma_B\cdot(T_C^4 - T^4),$$

- heating due to radiation

$$Q_T = \frac{\alpha}{2}\cdot\frac{\gamma+1}{\gamma-1}\cdot p\cdot\sqrt{\frac{R}{2\pi MT}}\cdot(T_C - T)$$

- heating due to residual gas

$$Q_S = L_S\rho\cdot\frac{dr}{dt},$$

- heating due to solidification

*Radius and temperature of jet in time of **t** are defined by equations:*

Cooling of liquid

$$a = a_0 - \frac{G}{\rho}\cdot t$$

$$a = a_0\cdot\exp\left\{-\frac{1}{2}\int_{Ttr}^{T}\frac{\frac{C_V}{L}dT}{1-\frac{1}{LG}\cdot\left[B\cdot\frac{T_C-T}{\sqrt{T}}\cdot p - \varepsilon\sigma_B(T_C^4 - T^4)\right]}\right\}$$

Solidification

$$\mathrm{T} = \mathrm{T_{tr}}$$

$$a = a_1 - \frac{G}{\rho}\cdot(t - t_1)$$

Cooling of solid jet

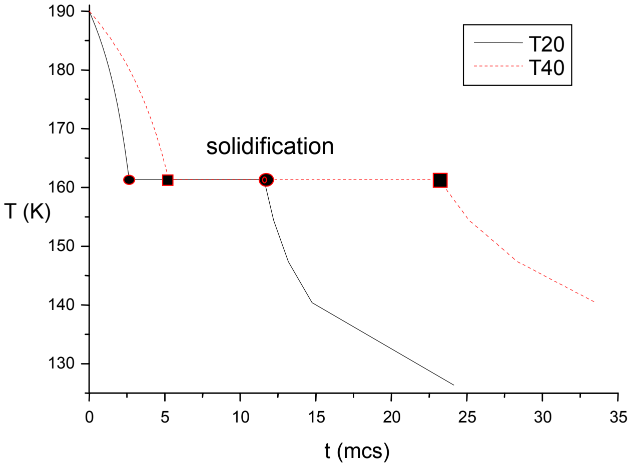
$$a = a_2\cdot\exp\left\{-\frac{1}{2L}\cdot\int_{Ttr}^{T}C\cdot dT\right\}$$

$$t - t_2 = -\frac{\rho}{2}\cdot\int_{Ttr}^{T}\frac{aC}{LG}\cdot dT$$

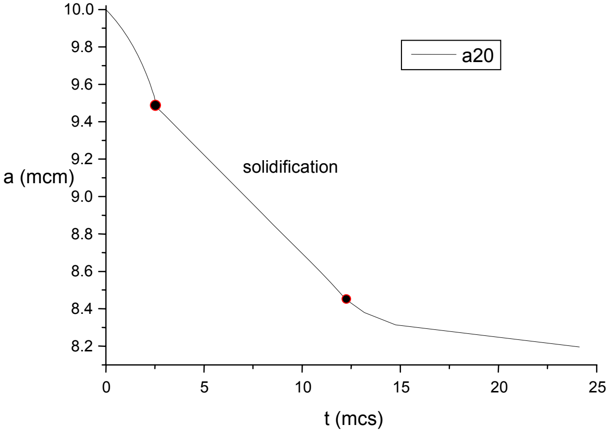
Theory and estimations

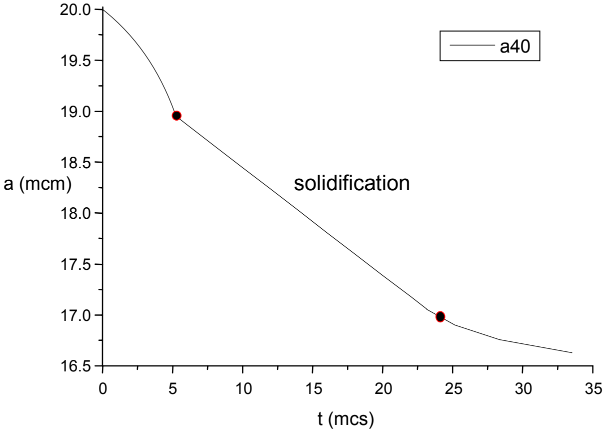
Behavior of a jet in vacuum

The average temperature of a jet and its radius depending on time for all stages of cooling



Average temperature of a jet depending on time for diameters 20 microns and 40 microns.





Radius of jet depending on time for initial diameters of 20 micron (at the left) and 40 micron (on the right).

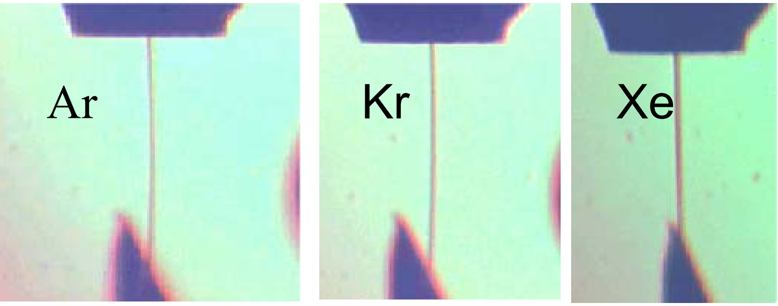
Experiments with a jet

Experiments with a vertical arrangement of a jet

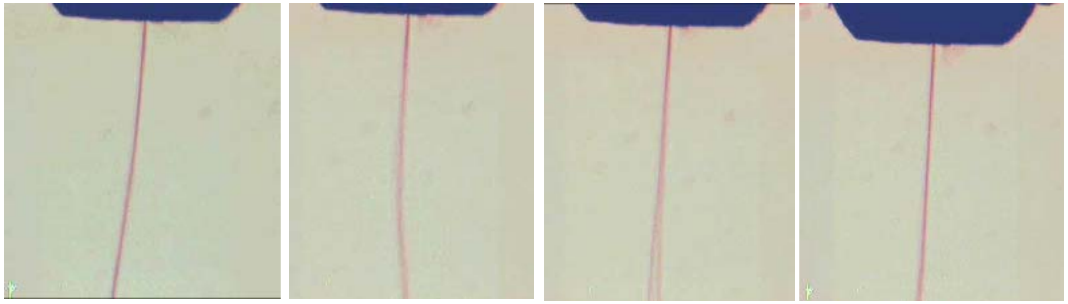
Experiments were developed for three inert gases - argon, krypton and xenon. As a result of experiments operating conditions of nozzle unit for different gases have been certain.

Parameter	Condensed gases		
	Argon	Krypton	Xenon
Temperature (K)	85 – 95	120 – 125	165 – 180
Pressure (atm)	1 – 8	2 – 4	2 - 6

A looks of a condensed gas jet



The video of a condensed krypton jet during the various moments of time.

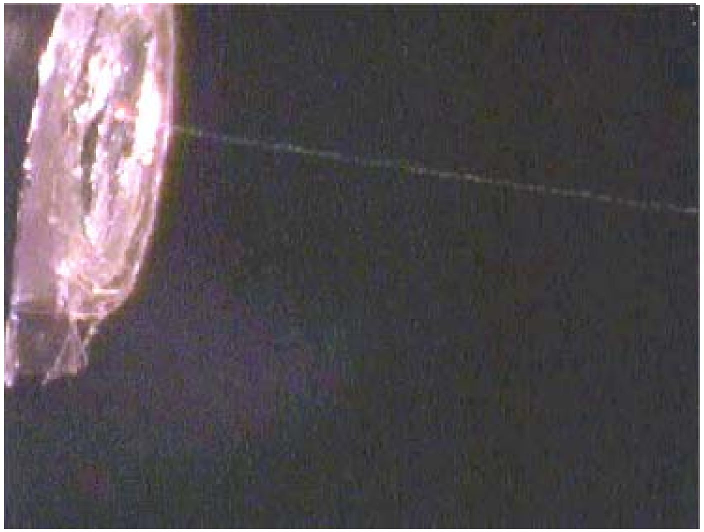


During work the outflow of jet was unstable in a direction of the motion; it chaotically changed on an angle up to ± 15^0. Diameter of a jet is 20 micron, length of a capillary - ~1 mm. On some frame it is visible that a jet bended. It is spoken that jet is solid.

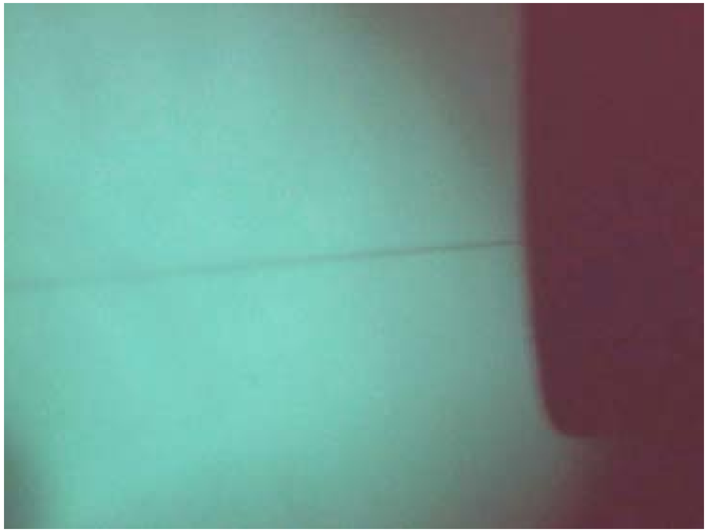
Experiments with a jet

Experiments with a horizontal arrangement of a jet

In this case it is used the short nozzle (diameter of 10 micron, length of 30 micron). Liquid velocity is about of 10 m/s. The jet is straight, but changes direction within the angle limits of 15-20^0. These changes of a direction are connected mainly with the solid microparticles getting in nozzle.



Kr (temperature 130-140 K, pressure 4-5 atm)

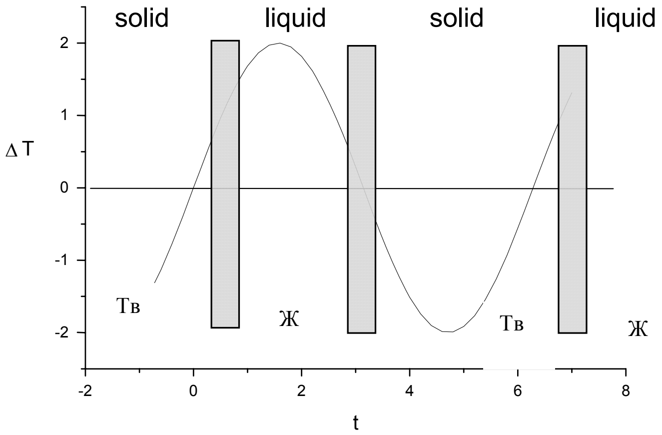


Xe (temperature 170-180 K, pressure 4-5 atm)

Experiments with a jet

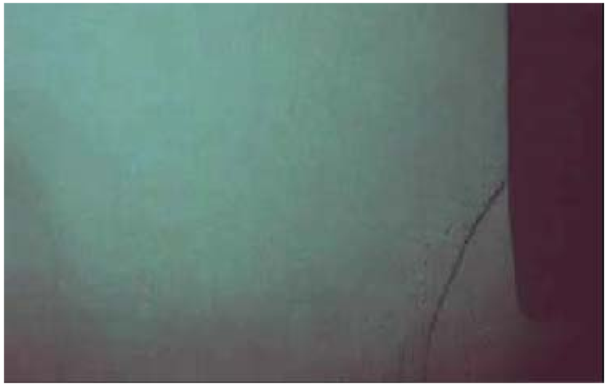
Experiments with a horizontal arrangement of a jet

Research of character of the liquid jet outflow depending on temperature



At automatic heat setting the temperature slowly changed concerning average value nearby of 181 K with amplitude about of 2 K. At pressure of 3 atm and temperature above 181 K the xenon jet was liquid and extended with the large velocity. At temperature below 181 K the jet freezed and moved with small velocity.

liquid



solid

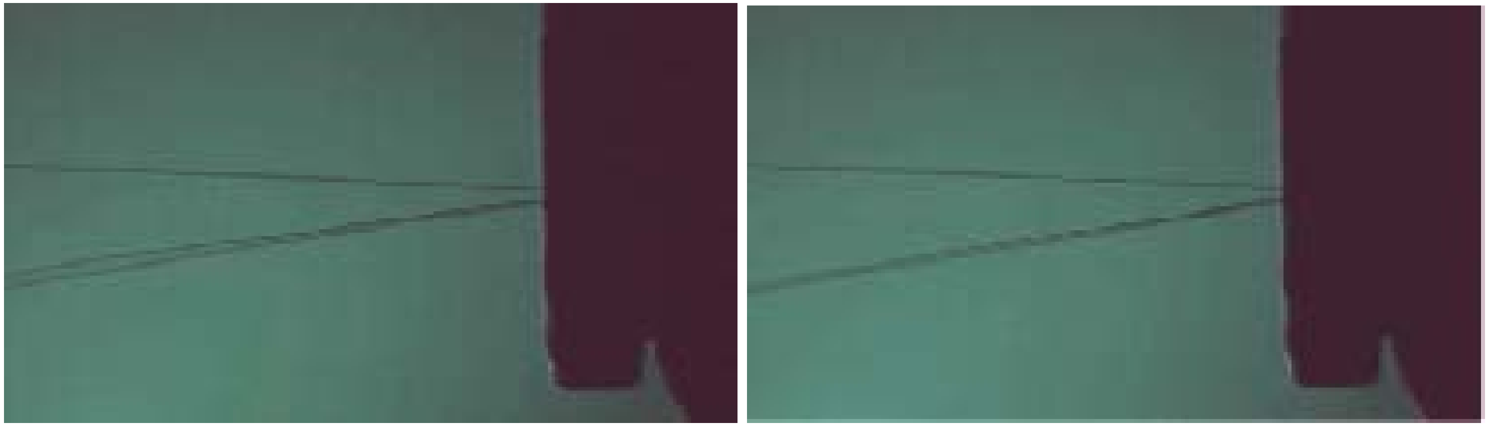
At increase of pressure the time of a finding of jet in a solid condition decreases and at pressure more than 8 atm the jet remained liquid all time.

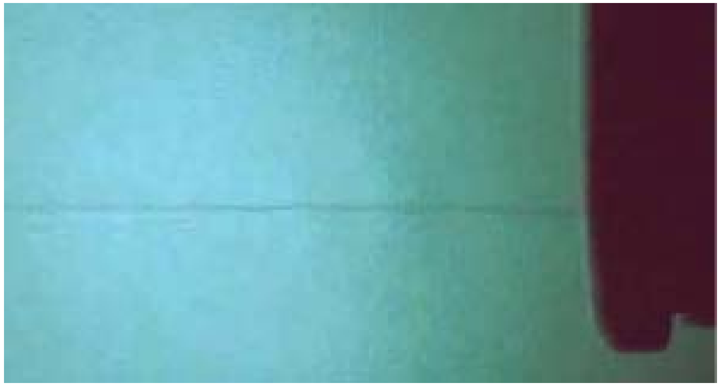
Experiments with a jet

Experiments with a horizontal arrangement of a jet

Studying work of nozzle containing three capillaries

Capillaries had diameter of 10 microns and were located on one straight line on distance of 20 microns from each other. It is visible, that jets deviate from each other. A parallel arrangement of all three jets to reach it was not success.



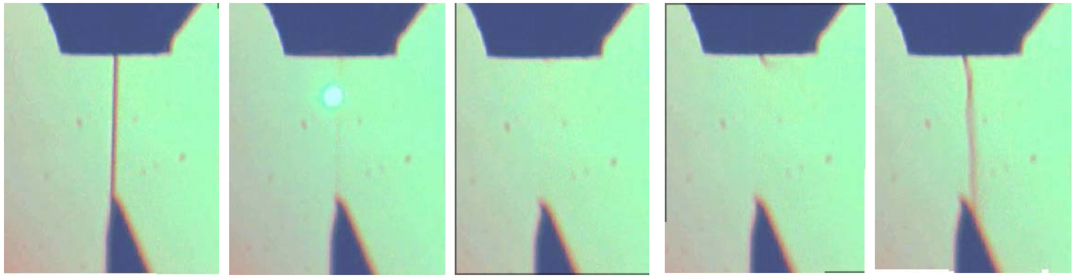


Research of jet behavior at various variants of nozzle unit and the condenser has allowed to choose an optimal operating mode and such device by means of which it became possible to generate liquid xenon horizontal jet stable during tens of minutes.

Experiments with a jet

Experiments on influence of the laser radiation on a jet

An experiment on influence of the laser radiation on a vertical jet has shown, that during an irradiation of a jet by powerful laser pulse on distance 1 - 1.5 mm from a capillary the failure of a jet is observed. The jet was solid and had small velocity of movement. The jet is restored through 1 - 2 seconds.



The long failure was not observed at research of radiation influence of the pulse-periodic laser on horizontal three jets. They were liquid and had greater velocity. The shooting rate is 30 frames per second at time of exposition about of 1 ms, frequency of laser pulse repetition - 25 Hz. Energy of radiation in an pulse is 0.05 J, a pulse duration is 10 nanoseconds.

Conclusion

- As a result of experiments the efficiency of systems of cooling, evacuation and maintenance of working temperature and pressure has been shown. The optimum design and operating mode have allowed to receive a jet of liquid xenon that was stable during several tens minutes. Studying of influence of laser pulses has shown that time of a jet restoration after impact of laser pulse makes much less than 0.01 s.

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