Classification of Atomization Devices

A Yu Vasilyev¹ E S Domrina¹ S V Kaufman¹,² and A I Maiorova¹

¹Central Institute of Aviation Motors named after P.I. Baranov, Moskow
²Moskow Institute of Physics and Technology

E-mail: vasiliev@ciam.ru

Abstract. Analysis of a great number of works allows concluding that many types of GTE and GTU nozzles can be divided into 3 main groups and 3 intermediate (composite) groups. The developed general classification of atomizers with descriptions of their operating principles, advantages and disadvantages is used to select a type of device for development. The most promising type chosen from descriptions given in the paper is the one with atomization of fuel by high-speed air flow.

1. Introduction

Nowadays a variety of atomization devices are used in gas turbine engines (GTE). All of them differ not only in design but also in the principles of fuel atomization. To simplify the selection of the type of the required atomization device in each particular case (for specific conditions of a combustion chamber), it is necessary to develop their classification. One of the main requirements to the atomizer is to provide a high-quality atomization of the fuel. The most logical way is to classify the devices in accordance with the type of conversion of fuel volume into a group of drops of air-fuel spray, i.e. in accordance with a type of atomization. The atomization types may be distinguished based on the energy used for the liquid atomization, i.e. the so-called “energy approach” [1-6] may be applied.

2. Classification of the atomizers

Fig. 1 presents a classification of atomizers divided into 3 main and 3 composite groups.

Three main groups:

• Hydraulic atomization is a process in which the energy of the liquid itself (natural oscillations of the jet, loss of stability) is used for its atomization.
• Mechanical atomization is a process in which the atomization of liquid occurs under external, not aerodynamic forces (acoustic resonators, electric fields, mechanical impact of the moving parts of the atomizer)
• Pneumatic atomization is a process in which the energy of air supplied to the atomizer from main compressor of the engine is consumed to atomize the liquid (atomization of various forms of liquid (jet or film) by airstreams).

Three composite (intermediate) groups:

• Combined mechanical-hydraulic atomization is a process in which both the energy of the liquid itself and that of a passive external source participate in atomization of the liquid (surface impingement).
• Combined mechanical-pneumatic atomization is a process in which not only the energy of the air supplied into the atomizer from the main compressor participates in atomization, but also...
that from an external source, including air of pressure higher than the one available in the engine (pneumatic atomizer of impingement type, bubbling nozzles, atomizers with air supplied from external source).

- Combined hydraulic-pneumatic atomization is a process in which the energy of both the liquid itself and the air supplied to the atomizer from the main compressor takes part in the atomization of the liquid (combined centrifugal-pneumatic atomizers).

The classification is valid only for similar “ideal” conditions, for example, for the operation of the atomizer in static gas medium. Otherwise, for impact during the operation of the centrifugal atomizer in the combustor, the fuel film could be destroyed by the high-speed flow before its own disintegration. Thus, the centrifugal atomizer belonging to the group of hydraulic atomization could shift to the group of pneumatic atomization.

The simplest in design atomizers are the ones of a jet type which belong to the group of hydraulic atomization. The fuel is supplied along the passage, and then flows through a simple cylindrical or shaped nozzle [7], at the exit of which the jet disintegrates into drops. The operation principles of the atomizers of this scheme are quite fully described in [8]. The advantages of this scheme are simplicity of manufacturing and low cost; and its disadvantages are narrow spray angle, deep penetration, and high density of aerosol which mainly consists of large drops. They are mainly used in afterburners and igniters [2].

To increase the spray angle, the atomizers with several nozzles (multi-jet) fed from a single passage [9] are used.

To widen the spray angle in one plane and to reduce the penetration, it is possible to apply slot atomizers. Such devices have a nozzle rectangular in cross-section (instead of the cylindrical one) and produce flat fuel sheet at the exit. Atomizers of this scheme and some semi-empirical dependences are shown in [10]; more detailed description is given in [11].

Next the most widespread atomizers of the hydraulic spray group are of the centrifugal type. The theory and methods of their calculation are described in detail in different works. However, one of the first works where the “principle of maximum flow rate” (the basis for the modern methods of centrifugal atomizers calculation) was set is [12].

![Figure 1. General classification of atomization devices.](image-url)
Later on this method was elaborated in [13], and its present-day version is presented in [14]. The simplest atomizer of this type is the single-passage centrifugal one (simplex) where the liquid before the nozzle exit is intensively swirled in a swirl chamber having been supplied to it through a row of tangential passages. Leaving the nozzle the liquid produces the sheet that becomes thinner with the growth of diameter and has approximately a conical shape. The sheet loses stability and disintegrates into drops. The advantages of this scheme include easy manufacturing, low cost, large spray angle, good atomization; and the disadvantages are the need in application of high-pressure fuel supply systems, excessive soot deposition, change in distribution of fuel in spray with the growth of pressure in the combustor and, consequently, the variation of temperature field uniformity depending on the engine operation mode. They are used in engines with narrow range of modes regarding fuel flow rates.

To widen the operation range of fuel flow rates of the atomizer without loss of the spray quality or rapid growth of fuel supply pressure, two-passage single-nozzle centrifugal atomizers (duplexes) are used. The main factor that distinguishes them from the single-passage ones is the application of two stages of fuel supply: pilot and main, i.e. two rows of tangential passages sequentially located in one swirl chamber. They swirl the fuel flows to be atomized at the outlet of the single nozzle, when interflowing into common film. The first stage of the atomizer initiated at the start-up mode due to the small area of tangential passages provides the acceptable fineness at this mode. The second stage is activated at a higher mode by the external valve located between the manifolds and provides the required flow rate. The main problem in the operation of this type of atomizers is that the fuel could flow to the off-stream passages resulting in carbon deposition. In other respects they have the disadvantages of the single-passage scheme and suit the combustors used in engines of low and medium gas compression ratios. The design peculiarities of such type of atomizers could be found in [15].

Finer adjustment of the flow rate and its wider range could be reached with the application of the atomizer with plunger. The spring-loaded plunger moves in a swirl chamber in such a way that in the deactivated atomizer only one row of tangential ports remains open but with pressure increase the plunger lifts opening sequentially new rows of the ports. The introduction of the plunger into design significantly complicates the atomizer and decreases its reliability. Such atomizers are employed in shipbuilding and marine GTU [2].

Further improvement in design of the centrifugal devices resulted in the development of two-nozzle two-passage atomizer [16]. They are called dual-orifice. In essence it is two single-passage atomizers fitted concentrically; i.e. inner passage totally separated from the outer one up to the nozzle exit. At low pressures (small flow rates) the fuel is supplied only through the inner nozzle, and with the pressure rise the distributing valve (located usually outside the nozzle – between the manifolds) opens and admits fuel to pass to swirl chamber and to the nozzle of the second stage. The annular sheets flowing out of inner and outer nozzles generate a united spray. The supply of the fuel to the second stage starts at the value of excessive pressure close to zero so the spray quality deteriorates with the activation of the second stage. The specific advantages of these atomizers are the acceptable fuel spray in a wide range of flow rates as well as the wide range of the stable combustion. But its additional disadvantages are higher susceptibility to passage blockage compared to the other atomizers, complicated design, including tighter requirements to manufacturing accuracy, and high production cost. It is a widespread type of the atomizers now and widely employed in combustors of different GTEs.

The last type of the atomizers attributed to the centrifugal ones is that with the fuel bypass (spill return) [17]. Unlike the single-passage (simplex) centrifugal atomizer it has a port at the bottom of the swirl chamber to bypass the fuel. Fuel is supplied under high pressure and of large flow rate and the flow rate passing to the combustor is adjusted by the bypass valve. The continuous high supply pressure provides a large swirl and appropriate atomization of the fuel at large and small flow rates. The pluses of such atomizers are the acceptable fuel spray within the wide range of flow rates, simple design, and low susceptibility to passage blockage because of their increased size. The minuses are the change in spray angle with variation of fuel flow rate, excessive requirements to the capacity of the fuel pump. They could be used for dealing with contaminated and thermally unstable fuels.
Following anticlockwise along the diagram with atomizers classification, it is necessary to analyze the group of combined mechanical-hydraulic atomization. This group includes the atomizers of impingement type [18] and their modification – atomizers with impinging jets. The principles of their operation and application are similar. The fuel injected under high pressure difference collides with a solid surface under an angle and spread into a flat sheet. The growth of instability causes the breakup of the sheet at some distance from the bottom edge of the solid body or at the edge itself generating a fuel volume that splits into fuel jets which in their turn disintegrate into large drops of different size. However, the formation of the drops starts since the moment of the liquid impingement to the surface (i.g.to the stationary external source). A part of fuel (depending on the angle between the jet and the normal) doesn’t spill over the plate but is reflected so this type of atomizers cannot be attracted to the hydraulic group. The advantages of the impingement atomizers is the simple design, possibility to generate a flat spray with short penetration and improved drop fineness compared with that of the slot atomizers. Their disadvantages are susceptibility to soot deposition and surface erosion, small range of fuel flow rates. Computations of sheet breakup for such an atomizer are presented in [3] basing on the work [19].

The atomizers with impinging jets [20] improve the fuel spray quality even more using the total impulse of impinging jets. The jets colliding at some angle with their axes usually lain in the same plane produce a flat sheet that disintegrates according to the principle described for the previous type of atomizers but due to the impulse composition and absence of friction loss at the surface, the obtained film has a larger relative velocity and is thinner that subsequently results in smaller size of drops. The remained disadvantages typical for the previous atomizer type are narrow operation range of fuel flow rates and at least doubled lower limit of fuel flow rate. This type of atomizers is sometimes used in liquid rocket engines both independently and within complex multilevel spray systems (as atomizers for main fuel supply); also they are employed in fire suppression systems.

The most widespread representatives of the mechanical spray group are two similar types of atomizers [21-22]: with rotating surface (rotary atomizers) and rotating shaft (slinger system). These two types mainly differ in the spray shape and area of application. In the atomizer with a rotary surface the liquid sheet is produced by rotation of a disk or a cup with liquid supplied to its inner surface. Flowing out the disk/cup edges this sheet becomes unstable and disintegrates into drops under the action of centrifugal force. Depending on the liquid flow rate and circumferential speed of the cup different mechanisms of liquid sheet breakup are activated [2]. At very small flow rates a liquid torus is produced at the cup edge, and then under the action of centrifugal force it is deformed by the bulges appearing on it. Their growth leads to the separation of drops from the cup edge. With the increase in flow rate these bulges at the torus transforms into thin strips, flowing out of the cup edge. The number of strips grows with the further increase of the flow rate and reaches some value after which it remains constant despite the value of the flow rate. The strips break up into the drops at some distance from the cup. With the further increase of the liquid flow rate, the strips (which number is constant) cannot accommodate the liquid so the torus converts into the sheet. At first this sheet extends from the edge but then disintegrates into ligaments and large drops. At very high circumferential speed the liquid reaching the edge of the cup immediately disrupts into small drops. In slinger system the fuel supplied through the hollow shaft is centrifuged off due to the shaft rotation.

Work [23] shows that the increase of rotary speed results in reduction of mean diameter of the drops, and the increase of fuel flow rate or its viscosity leads to the growth of the mean diameter. The advantage of this scheme is a possibility to use low-pressure fuel supply systems with satisfactory quality of atomization, the disadvantages are manufacturing complexity and small life time, slow response of the rotary speed to the change of the engine mode. These atomizers are used in small-size GTEs with low pressure ratio, and in chemical industry for atomization of viscous liquids and suspensions.

The next two types of atomizers practically are not employed in gas turbine engines so here we present only their brief descriptions. In ultrasonic atomizers the liquid is broken up under the action of fast vertical movements of a plate at the ultrasonic frequency. Standing waves are formed at the surface of the liquid supplied to the vibrating plate and the drops from the wave crests produce the spray.
Ultrasonic atomizers are mainly employed in medicine and different technological equipment (reactors, driers, etc.) [24].

During the electrical atomization the liquid jet is placed in the electric field. The pressure distribution on the jet surface created under this field causes the deformation the jet and results in the growth of instability, jet disintegration and formation of drops. The systems of electrical atomization of the fuels are also used in medicine and technology (spray painting, etc.) [25].

The analysis of the mechanical-pneumatic group of the atomizer should be started with the pneumatic atomizers of impingement type. The injected fuel jet impinges at some angle onto a solid surface and spreads out across it to form a flat sheet. The air passing for the pneumatic spray can impact the jet before its collision with a wall, or after its contact with the former or simultaneously with both of them [26]. The sheet is disintegrated under the action of the air at some distance from the bottom edge of the solid body or directly on the edge. However, drop formation can start at the moment of the liquid jet collision with a surface. A part of the fuel is reflected from the plate that doesn’t allow attributing this type of atomizers to the group of pneumatic spray. The merits of this atomizer-type are simple design, possibility to obtain the flat spray with short penetration length and improved fineness compared with the impingement atomizers. A drawback is possible erosion of the surface. A particular case of this atomizer type is the one where a jet collides not with a wall but with another jet. This type of atomizers is sometimes used in liquid rocket engines independently or within complex multilevel spray systems, e.g. [27].

It is necessary to note that there are acoustic atomization devices where the energy required for the liquid disintegration is supplied through the air flow, i.e. the liquid jet or sheet flowing out of the port or slot is impacted by ultrasonic vibrations of the air which the generator produce. The ultrasonic atomizers have found their use mainly in medicine and different technological devices [24].

The atomizers with air bubbling. In this type of atomizers air and fuel flows mix directly in the passages of the atomizer (under pressure) upstream the throat of the atomizer, i.e. the nozzle. The work [28] shows that depending on the air-fuel flow rate ratio the fuel flow could become an aerosol, be displaced to the wall or filling the whole volume contain the air bubbles. At the outlet of the atomizer due to the pressure drop the volume of the gas significantly increases breaking the liquid up into small but not monodisperse drops. The minuses of this atomizer type are low susceptibility to pulsation at some operation modes of the engine and the need to provide the high pressure for bubbling air supply. A plus is its potential to produce the drops of a very small diameter. In the process of design of this atomizer it is important to ensure two fluids to be well-mixed before the mixture reaches the nozzle of the atomizer.

The air-assist atomizers could be of different schemes similar to the ones for the air-blast atomizers. In their design the high-speed gas flow collides with the liquid flow of relatively low speed. The advantages of these atomizers are smaller diameters of the drops compared with the analogous schemes without the external air, and disadvantages - complicated design and need in auxiliary compressor to raise pressure of a part of the air flow. Such atomizers are usually applied for atomization of the fuels with high viscosity and the acceptable level of drop fineness is reached here regardless the liquid flow rate. The example of such an atomizer is a device used in the work [29].

The atomizer types that constitute the group of pneumatic spray require individual consideration as the most promising ones nowadays. Here we present only general provisions of the gas atomization basing on the following works: [1–6, 14, 30–34].

As it has been mentioned the operation principles of air-blast (pneumatic) atomizers and the air-assist ones (with external air source) are similar: the kinetic energy of air flow is used to shatter the liquid jet or sheet into liquid strips and drops. They differ mainly in the values of air flow velocity. The air-assist atomizers are fed by the air from compressor or high-pressure vessel so it is important to minimize the air flow rate. If there are no special restrictions on pressure value, the speed of the air could be significantly increased. Thus, the air-assist atomizers use small quantities of the air flowing at high speed. In air-blast (pneumatic) atomizers the velocity is usually limited by the value of ~120 m/s corresponding to the pressure difference at the flame tube wall so larger amount of air is required to
provide a high quality of atomization. After being used for fuel atomization the air is involved in the combustion process in the primary zone of the chamber.

Depending on the relative position of the fuel and air flows the atomization process could proceed according to the following different schemes. In pneumatic atomizers where the liquid jet or sheet is supplied to the coaxial gas flow, the unstable waves appear on the boundary between the gas and liquid; and the jet (sheet) breaks up into drops just as it was described above for the atomizers of hydraulic group but at shorter distances from the nozzle. In the pneumatic atomizer during the breakup of the liquid sheet flowing from the thin annular slot perpendicular to the air flow, the jet becomes deformed by the flow and disintegrates into drops depending on the flow velocity in the following way. In the absence of the air flow the generated film is not deformed and disintegrates along the periphery producing large drops. At the low air speed the film colliding with the air flow doesn’t break up immediately but is deformed and takes umbrella-like shape at the edge of which a thick unstable cylindrical rod is produced until it disrupts into the drops. With the speed growth the liquid film is disintegrated by disturbances and smaller drops are produced at its edge. At high speed the peripheral waves become dominant and the crests of small length are torn away to produce the droplets of small size (properly pneumatic atomization).

If the air flowing around the film is swirled relative to the film axis, it results in wider spray of the atomized liquid, improved distribution of drops in the space and drop-size reduction. When the gas flow runs perpendicular to the jet axis, some peculiarities arise which differ this disintegration from the one in concurrent flow [34-35, 37]. At the distance of several jet diameters from the port, the fuel jet is insignificantly disturbed. Downstream there is a section with large disturbances. Before its breakup the jet becomes flat under the action of the airstream and turns into a rather narrow sheet which later disintegrates into drops. Behavior of the liquid jet in the air cross-flow was studied in many works including [36-37].

The merits of the pneumatic atomizers in recent years have led to their wide use in industrial and aviation gas turbine engines. Most of the applied atomizers belong to the fuel prefilming type where the primary fuel film is later subjected to the action of the high-speed flow. In other designs the fuel is supplied to the air flow in one or several jets. In all cases it is important to use the spraying air efficiently.

The group of combined hydraulic-pneumatic atomization is based on the atomizers of centrifugal-pneumatic type. It is two-passage atomizers where one passage (usually pilot) operates according to the principles of a centrifugal atomizer described above, and the second one – with the use of atomizing airstream. The scheme of such an atomizer is presented on p.141 of the monograph [30].

The second type of atomizers of this group is those with air ejection. Such atomizers take the required volume of air from the environment. The fuel flow passing through the narrow section of the primary nozzle of the atomizer goes to a large volume of mixing chamber. The rarefaction created at the periphery of the jet during the sudden expansion allows ejecting the ambient air. Thus, the fuel jet interacts with air and atomization starts inside the atomizer, when the passage through the secondary nozzle (usually of larger section area) basically determines the shape of the spray. Usually such atomizers produce flat sprays (through the slot nozzle) or (rarer) solid-cone sprays (through the profiled nozzle of circular cross-section) [38]. The selection of an atomizer in every particular case depends on a number of factors. E.g. the type of the atomizer (hydraulic, mechanical or pneumatic) is dependent on maximum possible fuel pressure difference and on the ratio of the maximum fuel flow rate to the minimum one; the position and number of air passages (only outer swirler or flow stages) - on air pressure difference at the dome and ratio of fuel flow to atomizing air flow; penetration length, spray structure and spray shape - on the geometry of the combustor (a small and high combustor requires low penetration and large spray angle, the short one could demand slot atomizer, etc.).

Thus, the developed general classification of the atomizers with description of their operation principles, advantages and disadvantages of the separate schemes and entire groups could be used for selection of the type of the atomizer to be developed in each particular case.
Conclusion
The developed general classification of atomization devices with descriptions of operation principles, advantages and disadvantages of single schemes and their groups is proposed to be employed for selection of the atomizer type for further development during the designing of combustors for different operation conditions. According to the descriptions provided, one can conclude that the most promising devices for TJDE combustors designed today are low-pressure atomizers with pneumatic crushing of fuel.

During the development of new combined low-pressure pneumatic atomization systems for combustors of the advanced GTE it is necessary to take into account the aero-hydrodynamic foundations of pneumatic spray, schemes of interaction between fuel and airstream, influence of the atomizer geometry on the properties of the air-fuel spray. That in its turn requires the development of methods for calculation of two-fluid flows interaction as well as the systematization of fundamental study in the field of atomization of liquid fuels with air.

References
[1] Lefebvre A H and Ballal D R 2010 *Gas Turbine Combustion 3rd ed* (Bosa Roca, United States: Taylor & Francis Inc) p 558
[2] Borodin V A, Dityakin Yu F, Klyachko L A, Yagodkin V I 1967 *Atomization of liquids* (Moscow: Mashinostroenie) p 260
[3] Pazhi D G, Galustov V S 1984 *Foundations of liquid atomization technique* (Moscow: Chemistry) p 254
[4] *Handbook of Atomization and Sprays*, ed N Ashgriz 2011 (Springer US) p 935
[5] Khavkin Y I 2004 *Theory and Practice of Swirl Atomizers* (N Y: Taylor & Francis Books) p 406
[6] Chelebyan O G 2017 *The method of uniform air-fuel mixture preparing in the front device of low-emission aviation combustor* PHD dissertation Moscow Aviation Institute (National Research University) p 157
[7] Marshall W 1954 *Atomization and spray drying* Chemical Engineering Progress: Monography Series 2
[8] Kutovoi V A 1981 *Fuel injection in diesel engines* (Moscow: Mashinostroenie)
[9] Zavyalov N M 1953 TEKSO 1180/14
[10] Clark C L, Dombrowski N 1971 *Chem. Eng. Sci.* 26 1949
[11] Pazhi D G, Galustov V S 1979 *Liquid atomizers* (Moscow: Chemistry)
[12] Abramovich G N 1944 *Theory of centrifugal atomizer* Industrial aerodynamics (Moscow: Tcagi) pp 82–8
[13] Klyachko L A 1962 *Termal engineering* 3 25–7
[14] Dityakin Yu F, Klyachko L A, Novikov B V, Yagodkin V I 1977 *Atomization of liquids* (Moscow: Mashinostroenie) p 208
[15] Tipler W, Wilson A W 1959 *Turbines* Proceedings of the Congres International des Machines a Combustion (Paris) Paper B9 pp 897–927
[16] Kulagin L V 1962 *Papers of Railway Research Institute* 241 (Moscow: Transzheldorizdat)
[17] Carey F N 1954 *J R Aeronaut Soc* 58 737–53
[18] Belov I A and Kogtev R I 1967 *Journal of Engineering Physics and Thermophysics* 12 26
[19] Schlichting H (Deceased) and Gersten K 2017 *Boundary-Layer Theory* (Springer: Verlag Berlin Heidelberg) p 805
[20] Panevin I G 1960 *About liquid distribution in spray of impinging jets atomizer* Papers «Processes in Heat-engines» (Moscow: Oborongiz)
[21] Wehner H 1952 *Combustion Chambers for Turbine Power Plants* 7 395–400
[22] Hinze J O and Milborn H 1950 *ASME J Appl Mech* 17 145–53
[23] Dombrowski N and Munday G 1968 *Spray Drying, in Biochemical and Biological Engineering Science* 2 209–320
[24] *Power Ultrasonics* ed J A Gallego and K F Graff 2015 (Amsterdam: Elsevier) p 1166
[25] Luther F E 1962 Electrostatic Atomization of № 2 Heating Oil API Research Conference on Distillate Fuel Combustion API Publ 1701 (Paper CP62-3)

[26] Vasilyev A Yu, Sviridenkov A A, Yagodkin V I 2007 Proceedings of IX International Conference Optical Methods of Flow Investigation, Moscow, MPEI (TU) 60–3

[27] Vasilyev A Yu, Maiorova A I, Sviridenkov A A, Tretyakov V V, Furletov V I, Yagodkin V I and Goltshev V F 2005 Materials of 2nd International Conference Heat and Mass transfer and Hydrodynamics in swirling flows, 15–17 Mach 2005, Moscow, MPEI (TU) on CD rn 0320500321

[28] Kleinstreuer C 2017 Two-Phase Flow: Theory and Applications (New York: Taylor & Francis Inc) p 512

[29] Mullinger P J and Chigier N A 1974 J. Inst. Fuel 47 pp 251-61

[30] Lefebvre A H and V G McDonell 2017 Atomization and Sprays 2nd Edition (Boca Raton: CRC Press) p 312

[31] Vasil’ev A Yu, and Mayorova A I 2014 High Temperature 52 252–61

[32] Vasil’ev A Yu, Maiorova A I, Sviridenkov A A and Chelebyan OG 2018 Journal of Engineering Physics and Thermophysics 91 1475–85

[33] Vasilyev A, Zakharov V, Lyashenko V, Medvedev R, Chelebyan O, Maiorova A 2018 Proceedings of ASME Turbo Expo 2018 June 11–15, Oslo, Norway (Paper GT 2018-75419)

[34] Raushenbakh B V at al. 1964 Basic Physics of the Processes in Combustors of Air-breathing engines (Moscow: Mashinostroenie) p 522

[35] Gizatullin R N, Kaufman V I 1983 High Temperature 21 209–13

[36] Muppidi S, Mahesh K 2005 Journal Fluid Mechanic 530 81–100

[37] Maiorova A, Sviridenkov A and Tretyakov V 2010 The investigation of the mixture formation upon fuel injection into high-temperature gas flows Fuel Injection Ed D. Siano (Rijeka, Croatia: Sciyo) 7 pp 121–42

[38] Averkin A G, Panov E A, Fedin S V, Orlova N A 1999 RF Patent № 2135892