FLOW INVESTIGATION IN PUMPING LOOPS OF GAS LASERS

A. I. Zhidovich, L. G. Zhukhovitskii, and I. G. Osipyan

UDC 621.373.826

A simple method of flow visualization is shown to be effective for optimization of pumping loops of gas lasers. The results of an experimental study of flows in the closed-pumping loops models are reported.

One of the main problems in the design of the gas-flow lasers is the creation of a closed pumping loop of a working medium. At present the loop using a diametral-flow is recognized to be the most effective design [1]. An advantage of this design lies first in the similar cross sectional shapes of fan channels and a laser discharge chamber which makes it possible to transform the loop cross section with respect to only one coordinate. As a result, it allows an appreciable decrease in the overall dimensions of the laser as compared to other designs. Besides, the diametral-flow fans possess extraordinary input–output characteristics [2]. Being basically two-step fans (a gas twice passes through a vane array), diametral-flow fans develop a higher pressure than centrifugal- and axial-flow ones and retain stable operation at heavy throttling of the loop until complete overlapping of the pass cross section [3]. This feature is of particular importance for laser pumping loops which show, as a rule, a high aerodynamic drag. It should be noted, however, that not all the diametral-flow fans have operating characteristics suitable for laser pumping loops. Engineering methods of their developing and designing are not available nowadays. Present-day theoretical research studies are based on mathematical models which do not take into consideration the specific aerodynamic features of diametral-flow fans at full length. Therefore all work aimed at creation of a particular design are presently conducted experimentally [3].

When a fan operates in a complex-geometry closed loop, it is necessary to take account of the interaction of flows formed in the fan and in the pumping channel. The diametral-flow fan characteristics very much depend on the direction and velocity of inlet flow [4] as well as on a shape of a fan body and arrangement of inlet and outlet pipes [3] which, in turn, are dependent on general lay-out of a pumping loop. On the other hand, the velocity and the direction of the fan outlet flow must be in accord with the parameters of a pumping tract and the elements arranged in it.

Thus, the development of a laser pumping unit is not closed by designing a fan with certain input-output characteristics, it requires optimization of the entire pumping loop. A complicated pattern of the flow in a diametral-flow fan and a strong influence of numerous factors on its characteristics have hindered the understanding of physical processes occurring in it. The works of some researchers [5-7] have resulted in the optimal procedure which allows the investigation of specific operating features of different fans and the design of fans with the desired characteristics. The procedure consists of preliminary fan flow visualization and obtaining the data on processes occurring in the fan. At the second stage, the preliminary visualization results are employed to choose a fan scheme and to study its operation to obtain quantitative characteristics. Though the visualization results are mainly of qualitative nature, they considerably simplify the flow investigation in diametral-flow fans and allow the development of its concrete designs. Since the diametral-flow fan flow is two-dimensional, the method of a light or laser "knife" is widely used for its visualization. It consists of creating a plane light beam ("a knife") transversing a transparent fan model and lying in the plane of the main flow. Particles entrained by the flow leave illuminous traces (tracks) in the "knife" plane which are recorded by a high-speed camera. It is difficult for rather coarse particles to suspend in the flow, therefore we have conducted experiments in a fluid by using a hydraulic analogy method. The method is based on the analogy between the equations for inviscous incompressible fluid flow in an open channel and the equations for two-dimensional potential gas flow. Instead of a study of gas flows around different bodies, these bodies are investigated in a water flow in a flume. The analogy methods do not allow simulation of viscosity forces, therefore the results produced by them somewhat differ from real data. An important merit of the analogy method is the simplicity of the experimental set-ups and the experiments themselves. The experiments conducted

---

Research Institute of Nuclear Problems, Belorussian State University, Minsk, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 63, No. 1, pp. 38-43, July, 1992. Original article submitted June 13, 1991.

 1062-0125/92/6301-0680$12.50

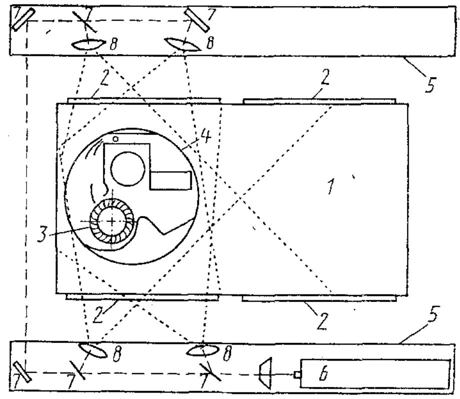

Fig. 1. Schematic of the flow of the visualization facility (the dotted line indicate boundaries of laser "knives").

on these set-ups are aimed mainly at qualitative estimation of models. The best models are selected and then used for further investigation on aerodynamic test benches to obtain exact quantitative relations [8]. A positive feature of the hydraulic analogy method is its visualization. The method makes it possible to reveal specific features of flow patterns and revise design parameters of a concrete unit. This procedure is particularly convenient for investigating the closed pumping loops since it allows visualization of the effects related with mutual influence of the elements of a loop and a fan. In the majority of cases it becomes evident how to optimize the loop when visualizing the flow patterns.

A visualization facility is shown schematically in Fig. 1. Flume 1 represents a rectangular 0.8 × 1.5 m tank with a depth of 0.45 m. Its side walls have windows 2 made of organic glass. Under the flume bottom there is a dc motor with a reduction gear whose shaft is inserted via a seal into an inner volume of the flume. A model of rotor 3 is mounted vertically on the shaft. On the same level with a lower flange of the rotor, a false bottom is installed on which the transparent model of test loop 4 is fixed. Near the flume, there is an optical bench 5 which mounts the argon laser LGN-406 6. The optical system of splitting and turning a laser beam ensures illumination of a test object from four sides. Laser "knives" are formed by tilting mirrors 7 and short-focus cylindrical lens 8. The system provides uniform illumination of a test region including the inner cavity of the rotor. As particle-trackers, use has been made of 0.5-0.7 mm diameter spheres made of transparent clear polystyrene whose density is close to that of water. Velocity distribution in the flow is determined by a length of tracks at a recorded exposure time.

The experiments have revealed that some particle-trackers intersect an illuminated plane at an angle that shortens their tracks and leads, naturally, to errors in velocity determination of a given particle. In order to find these tracks, we have incorporated a laser beam splitter in the form of a slotted disk into the optical scheme of the flow visualization facility. Splitting a beam imparts the tracks in the form of dashed lines. At a certain shutter speed and a stable speed of splitter rotation the number of dashes on the tracks in the illuminated plane must be the same. A decrease in the number of dashes points to intersection of the "knife" plane by a particle. A dotted character of tracks considerably simplifies the computer-aided processing of flow patterns. Besides, the possibility arises to determine three-dimensional flow zone and to evaluate an axial flow in these zones.

The present paper offers the results of research studies aimed at optimization of the pumping loops of "Lantan" and MLT-1.2 CO_2-lasers. A technological "Lantan" CW laser designed at the Institute for Mechanics Problems (IMP) of the former USSR Academy of Sciences is distinguished with high reliability, effective arrangement, and long service life. At present the laser enjoys quantity production, although ways are being sought for further improvement and, above all for increasing its output power. The research studies conducted at the IMP have demonstrated that power may be increased only for a short period of time because of overheating of a working medium.

A pumping loop of a "Lantan" laser is made in the form of a closed wind tunnel with a constant-width cross section (Fig. 2a). Discharge chamber 1 of the laser is positioned in the upper rectangular channel between confuser 2 and diffuser 3 sections. The lower rectangular channel houses two heat exchangers 4, between which two axial-flow pump units 5 are installed in parallel. The rectangular channels are interconnected via turning runs of gas track 6.

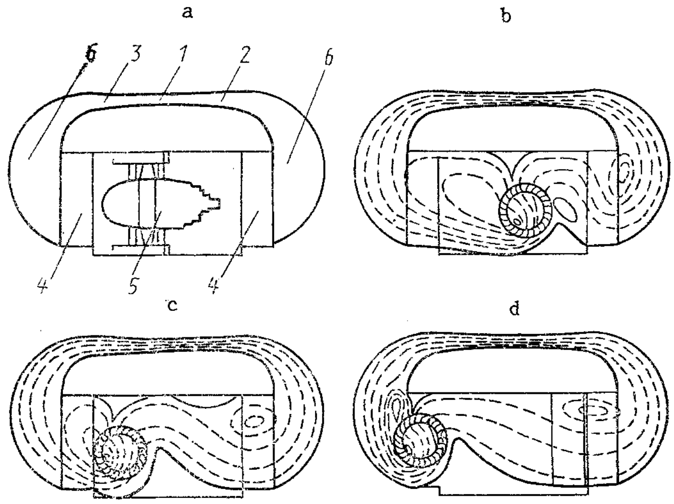

Fig. 2. Variants of the pumping loop schemes of the laser "Lantan": a) initial pumping loop; b) scheme with a running diametral-flow fan in the rectangular channel of the loop; c) intermediate position of the diametral-flow fan; d) diametral-flow fan in a turning section of the loop.

The use of axial-flow pump units in the pumping loop "Lantan" provides a working medium velocity in an active section up to 70 m/sec, while an increase of a radiation power up to 5-7 kW requires $\approx$100 m/sec. Besides, when the pump units are installed in parallel, the flow uniformity and stability deteriorate to exert unfavorable influence on the radiation quality. The required improvement of flow characteristics in the loop may be achieved by using the diametral-flow fans instead of axial-flow ones.

Proceeding from the condition of minimally changing the design of the laser pumping loop "Lantan" to be modernized, it is most desirable to install a diametral-flow fan in the rectangular channel between the heat exchangers, i.e. instead of the axial-flow fans. Therefore, a diametral-flow fan must be of a running flow-type or with a slight change in the turning angle of the flow. However, the required input–output characteristics of fans are typical mainly of those having a turning angle close to 180° [3, 7]. Such a fan with its opposed inlet and outlet branch pipes may be installed in the rectangular channel only in the case when the used diametral-flow rotor has its outer diameter no more than 1/3-1/4 of the channel height, i.e. 130-160 mm. In manufacturing the rotor with relative elongation $L/D > 5$ ($L = 1$ m is a length of the vane array along the axis of rotation) encounters essential engineering difficulties concerned with the necessity of providing the strength of long thin vanes are encountered. Besides, the loss stability and the vortex core failure were observed in long rotors [9] which resulted in a decreased efficiency and deterioration of the flow quality. Also, it is unclear how to accomplish the mating of narrow ($\approx$100-120 mm) branch pipes and heat exchangers.

Based on the above reasons, we decided to design a high-pressure diametral running flow fan to be positioned in the turning channel of the loop.

The basic flow fragments in a diametral-flow rotor (recirculation flow, inlet and outlet jets) may be encompassed by a circumference with its diameter of $\approx$2D, therefore the rotor diameter D is chosen equal to 260 mm. Proceeding from the overall dimensions of the flume, a simulation scale was taken 1:2.6 and a diameter of the rotor model was 100 mm.

The initial design of the fan body which was developed was based on the flow pattern data and relations between the geometric parameters of the body elements of diametral-flow fans as well as on the experimental data obtained earlier. It was anticipated that an increase in the volume occupied by a recirculation zone would allow a change in the direction of the flow outlet jet with simultaneous widening of its cross dimension to more effectively use a heat exchanger section and to preserve, at the same time, the position and the behavior of a vortex core inherent to the fan with the 180° flow turn.

Indeed, such a fan makes it possible to realize a strongly diverging outlet jet which transverses a larger part of the heat exchanger cross section. However the flow velocity in the working zone (the discharge chamber channel) is low, i.e. about 0.6-0.7U. Continuous illumination of the observation volume of the trackers as well as scanning the volume by "a laser knife" have revealed that there are three dimensional return jets in the end zones of the outlet flow which are directed towards the recirculation zone. A considerable part of the outlet flow is closed via these jets. Previous experience shows that such a flow

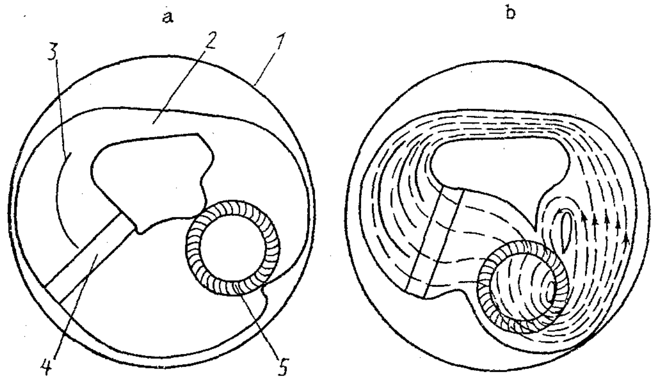

Fig. 3. Schematic of the pumping loop of a laser MLT-1.2: a) initial arrangement [1, body; 2) active section; 3, guide vane; 4, heat exchanger; 5, diametral-flow rotor]; b) schematic of the modernized loop and the flow pattern in it.

pattern develops at the threshold of a presurging regime. This conclusion was confirmed by further experiments in which the pumping loop resistance or the fan body shape underwent slight changes. In this case, a vortex core lost its stability, acquired a curved form, and began to process in the internal zone of the rotor; the flow in the working zone ceased motion, changed its direction for the reverse, then the flow patterns recurred cyclically.

Visualization has revealed some elements of the design which cause flow instability. A slight change in a shape of these elements considerably changes the flow pattern: a vortex core gets levelled in a vertical direction and stabilizes, the return flow jets in the end zones disappear, the velocity in these zones increases up to 1.06U (Fig. 2b). Further improvement of the flow quality, as seen from the figure, may be achieved by eliminating the return flow near the upper edge of the fan body. For this purpose the pitch of the rotor was increased and the fan was displaced downward the flow (Fig. 2c). As compared to the previous arrangements, the vortex formation in the pumping tract appreciably decreased, the flow became more ordered. The flow velocity in the working zone attained 1.4U. On the other hand, a considerable drawback of this arrangement is a small cross section of the fan outlet jet which decreases the efficiency of the outlet heat exchanger and leads to considerable dissipative losses in it. Therefore we decided to take the heat exchanger away from the fan outlet jet and to place the fan in a turning channel of the loop by using the fan body design which allows the flow to turn by 180° for this purpose. This made it possible not only to increase the efficiency of the heat exchangers but also to increase the flow velocity in the working zone up to 1.8U. Analysis of the flow pattern shows that the loop characteristics may be further improved by installing the turning vanes in the channel in front of the heat exchangers as well as by decreasing a heat exchanger height and organizing uniform flow at the fan pipe inlet. Also, the fan design may be made more perfect by choosing an optimal shape of the lug, the rear wall, and the fairing. However it is more expedient to carry out these works on a gas stand.

Analogous experiments were conducted on the pumping loop model of a MLT-1.2 laser developed at the Institute for Flow Machines of the Polish Academy of Sciences. Unlike the previous design, this loop has a cylindrical lay-out with a diametral-flow fan (Fig. 3a). Measurements made on the operating laser have shown that the gas mixture flow in the working zone does not possess the required velocity and uniformity. The attempts to elucidate the reasons of such a situation by measuring the velocity fields in the loop and on a specially manufactured aerodynamic test unit have failed to produce the desired result.

Flow visualization in the loop model on the hydraulic test unit has shown that the fan operates in a presurging regime: a velocity profile with respect to a channel width has a W-form, the flow is unstable in time and its velocity in the working zone is low. As in the previous case, we cannot offer a photo or a drawing of the flow pattern in the initial loop arrangement because of the flow three-dimensional character and its instability. Visualization was performed at continuous illumination of the model volume.

Based on the obtained data and available information on the influence of the loop elements and the fan on a flow pattern, some changes were made in the initial design shown in Fig. 3b. We succeeded practically at once in obtaining the uniform and stable flow with a high pumping rate in the working zone. In the flow, there are some insignificant small-scale defects in the region of the lug near the upper edge of the cowling and at the turnable array inlet . Elimination of these defects on the hydraulic test unit is not expedient since this model insufficiently completely takes into account the real laser loop characteristics. However, the discovery of these defects enables one to concentrate attention on the zones which need particular care during tests and debugging the design.

The reported results show that the preliminary flow visualization in the models of laser pumping loops considerably simplifies the work and makes it possible to avoid mistakes at the stage of developing and designing a laser. The design procedure is very simple and the consumed time and capital outlays are incomparably lower than those related with adapting a loop from the unsuccessfully designed one. In modernizing the available lasers, hydraulic modeling is an effective tool for obtaining the desired result with minimally changing the design.

NOTATION

D, inner diameter of the vane array of the rotor; L, length of the vane array along the axis of rotation; U, peripheral velocity of the rotor.

LITERATURE CITED

1. F. E. Kassadi, Aérodinamicheskaya Tekhnika, No. 7, 135-148 (1986).
2. T. P. Balmer, Design News, No. 9, 20-23 (1966).
3. A. G. Korovkin, Prom. Aerodin., No. 1(33), 71-80, Moscow (1986).
4. S. M. Grigor'ev and G. A. Gridneva, Zap. LSKhI, **149**, No. 1, 76-86 (1970).
5. B. Eck, Fans, Pergamon Press, Oxford (1973), pp. 156-181.
6. K. Yamafuji, Bull. JSME, **18**, No. 123, 1018-1024 (1970).
7. A. M. Porter and E. A. Markland, J. Mech. Eng. Sci., **12**, No. 6, 421-431 (1970).
8. N. N. Suntsov, The Analogy Methods in Aerohydrodynamics [in Russian], Moscow (1986).
9. D. J. Allen, Conf. on Fan Design and Application, Guildford. England, Sept. 7-9 (1982), pp. 355-386.

THE KINETIC MODEL OF PARTICLE TRANSFER IN TURBULENT FLOWS WITH CONSIDERATION OF COLLISIONS

L. I. Zaichik

UDC 532.529

The work presents the kinetic model of particle dynamics in turbulent flows taking into consideration inelastic collisions. Transfer coefficients of the dispersed phase in constrained flows are found on the basis of this model.

To describe a particle movement in rarefied dispersed flows (i.e. for low volume concentration of the dispersed phase), greater attention should be paid to the interaction between particles and turbulent pulsations of the carrier flow, since the role of collisions between the particles proper is not essential. The kinetic equation for the probability density function [PDF] of the particle velocity in turbulent flows without taking account of collisions was obtained in [1, 2]. For large particles ($\tau/T >> 1L$) in an isotropic turbulent flow this equation develops into the known Fokker–Planck equation for the Brownian movement [3, 4]. A solution of the equation for the PDF can be constructed with the help of the perturbation method [4-6] widely used in the kinetic theory of gases for the solution of the Boltzmann equation [7, 8]. On the contrary, in the case of the analysis of particle dynamics in sufficiently dense dispersed flows the collisions of particles between themselves play a determining role. An elementary kinetic theory of highly concentrated dispersed systems is formed in [9]. Studies [10, 11] offer the kinetic models of particle transfer in dispersed flows, based on the solution of the Boltzmann equation by the perturbation method and further developing

Krzhizhanovskii Moscow Power Engineering Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 63, No. 1, pp. 44-50, July, 1992. Original article submitted May 13, 1991.

1062-0125/92/6301-0684$12.50