CONCEPT OF A SWIRLING DIFFUSER IN BATCH BLENDING TANKS

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ABSTRACT: The mixing of two or more components belongs to the category of the most common unit operations, both in technology and in nature. One particular version is homogenization (blending), the effectivity of which is strongly related to the blending time. Among many differentiated individual solutions of mixing systems used in blenders, one should distinguish the class of agitators with diffusers. An analysis of the character of the velocity field during a blending chamber operation leads to the conclusion that it would be of avail to outfit a straight diffuser with different setup of elbows. In consequence, the vertical direction of the inflowing fluid stream would be changed into the horizontal direction of the outflowing stream, which should intensify the blending process. The concept has been verified experimentally, making use of the tracer methodology. The obtained results confirmed the theoretical conclusion, that the blending time for the swirling-diffuser was shorter than for the classical straight one.

KEY WORDS: batch blending chamber; swirling diffuser; blending time

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ABSTRACT: The mixing of two or more components belongs to the category of the most common unit operations, both in technology and in nature. One particular version is homogenization (blending), the effectivity of which is strongly related to the blending time. Among many differentiated individual solutions of mixing systems used in blenders, one should distinguish the class of agitators with diffusers. An analysis of the character of the velocity field during a blending chamber operation leads to the conclusion that it would be of avail to outfit a straight diffuser with different setup of elbows. In consequence, the vertical direction of the inflowing fluid stream would be changed into the horizontal direction of the outflowing stream, which should intensify the blending process. The concept has been verified experimentally, making use of the tracer methodology. The obtained results confirmed the theoretical conclusion, that the blending time for the swirling-diffuser was shorter than for the classical straight one.

1. INTRODUCTION

Mixing is one of the most common unit operations, beginning with natural phenomena, through different branches of industry, up to everyday life. The essence of mixing processes is the mutual spreading of at least two substances. They must have a fluid form or must be comminuted (into grains of solids, liquid drops or gas bubbles).

One should distinguish the basic elements of the process, leading to the final effect - advection or convection (macro-scale), spreading by turbulent vortices and local shearing (meso-scale) and molecular diffusion (micro-scale). Advection takes the form of a translatory motion (e.g. during the transfer of pollutants in a river) or a returnable flow. A second kind of circular motion should be recognized as a basic form of advection during mixing. It is generated by some kind of impeller (including pumps) and is called agitation or stirring. In both cases, the effectivity of advective mixing can be strengthened by the installation of special partitions in the mixing system (e.g. the mixer labyrinth or baffled tanks).

In practice, a huge number of particular solutions of mixing systems exist. Therefore, characterizing each one of them would be aimless for the purpose of this work. The more so that in the problem bibliography for some time past one can distinguish two currents: first one undertaking general questions like experimental techniques (e.g. [2, 3]) or the influence of the mixing chamber shape (e.g. [11,15]); second one devoted to the specialized aspects of the different technical branches (e.g. [6, 7]). This paper contains a proposal of the first kind. For a general handling of the subject one should remember that the basic classification of

impellers is determined by the predominant pattern of the flow induced in the chamber, and by the fluid viscosity. One can distinguish the following flow components [22]:

- radial (e.g. turbines);
- tangential (e.g. frames, anchors);
- axial (e.g. propellers, helical agitators).

An agitating structure (one or more, positioned on the same shaft) can be placed directly in a chamber ("open impeller"). However, some devices which generate axial motion can be built up by a diffuser, i.e. by a segment of a pipe, parallel to the shaft ("impeller with a diffuser"). Such a solution improves the vertical flow conditions, intensifying the axial circulation. The aim of this paper is a presentation and experimental verification of some modifications of this variant.

A quantitative description of the functioning of blending chambers on a theoretical basis is a very complex topic. Therefore, in practice numerical or physical experimental methods are commonly applied for this purpose. In order to generalize the phenomenon description obtained by means of experiments, the mixing operation can be described by some empirical functional relations [22]. Particular unit factors influencing the final result of mixing or blending are expressed by dimensionless criteria numbers. One of such numbers expresses the dimensionless blending time t_B:

$$N_B = t_B\, n, \tag{1}$$

which is a crucial parameter characterizing the considered phenomenon.

In a simplified theory of mixing this value is treated as a constant, which must be determined individually for each object. According to more sophisticated approach, N_B can be calculated e.g. from the relation [5]:

$$N_B = 16.95\ (D/d)^{-1.67}(d/H)^{-0.5} \tag{2}$$

or [10]:

$$N_B = 4.8\ (d/D)^{0.82}\, Re^{0.167}\ ,\ \ Re = D^2 n/v, \tag{3}$$

where: n – rotational speed of the impeller, v – fluid kinematic viscosity, D – impeller diameter, d – mixing chamber diameter, H – chamber depth.

However the paper is devoted to the blending tanks fitted with a diffuser. This means that the dominating part of the circulation energy is delivered by the submerged stream leaving diffuser and the system is working as a jet mixer [13]. If so, the parameter N_B can be calculated using the following relation [8]:

$$N_B = 2.95\ Z^2 n/U\delta\ . \tag{4}$$

The initial mean jet velocity U is equal to:

$$U = 4Q_p/\pi\delta^2 \tag{5}$$

and the propeller discharge Q_p can be expressed by the formula proposed by Nagata [16]:

$$Q_p = 0.78nD^3. \tag{6}$$

The jet length Z in the considered case (Figs. 2, 4) is equal to the circular distance from the diffuser outlet to the back-side of the elbow:

$$Z = \pi(d - \delta). \tag{7}$$

Substituting Eqs. (5,6,7) into Eq. (4), after some evident rearranging, one obtains:

$$N_B = 29.3 \, (d - \delta)^2 \, \delta \, / \, D^3. \tag{8}$$

It is worth noticing that the possibilities of blending phenomenon examination existing in this field at present are very broad [2]. Especially methods of flow visualization are utilized with a good outcome. An example of such approach is the observation of the intensity of a color during the blending of an acid and a base with a pH-indicator [12]. In the present form of this method the distribution and the final uniformity of the dye are not determined by simple recording of the color intensity but by the precise measurements. The first step of this procedure is the injection of a dye into the tank. As an especially convenient tracer, a solution of a Rhodamine WT can serve. It is an organic substance, which activated by the light with a wavelength 553 nm, emits the light with a wavelength 627 nm (luminescence) [20]. The fluorometric sensor contains both the source of the light and the receiver, which measures its intensity, proportional to the tracer concentration. This effect opens the doors to precise determination of this important value. In the presented case it was possible to measure the concentration between $0 - 1000$ ppb. This method is very convenient and enables experimental investigations of many different fluid-flow objects and systems, both natural and technical [18, 21].

Among the important elements of the presented investigations, one should underline the physically objective balance of the power delivered to the system P and the power of dissipation P_D. In a steady state these powers are identical [1]. The power of dissipation can be expressed by means of the velocity field non-uniformity, according to the classical relation describing the energy dissipation rate distribution (when the fluid density is constant, in a cylindrical coordinate system [19]):

$$\varepsilon = 2\mu \left\{ \left(\frac{\partial v_r}{\partial r}\right)^2 + \left[\frac{1}{2}\left(\frac{\partial v_\theta}{\partial \theta} + v_r\right)\right]^2 + \left(\frac{\partial v_z}{\partial z}\right)^2 + \frac{1}{2}\left(\frac{\partial v_\theta}{\partial z} + \frac{1}{r}\frac{\partial v_z}{\partial \theta}\right)^2 + \right.$$
$$\left. + \frac{1}{2}\left(\frac{\partial v_z}{\partial r} + \frac{\partial v_r}{\partial z}\right)^2 + \frac{1}{2}\left[\frac{1}{r}\frac{\partial v_r}{\partial \theta} + r\frac{\partial}{\partial r}\left(\frac{v_\theta}{r}\right)\right]^2 \right\} \tag{9}$$

where r – radial distance, θ – angular coordinate, z – height, v_r – radial velocity, v_θ – angular velocity, v_z – vertical velocity.

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The form of Eq. 9 gives reasons for the concept of differently shaped diffusers, presented below, as it shows that the more differentiated velocity field (i.e. the more the velocity derivatives in Eq. 9 differ from zero), the better is mixing effectivity.

2. THEORETICAL ANALYSIS AND PRACTICAL PROPOSAL

As it was already mentioned, the structure of Eq. 9 shows that the more differentiated the fluid velocity field in a blending chamber, the greater the effectivity of this process. By analyzing particular technical solutions one can evaluate the character of a velocity field in each case. Generally, it is worth noting that the biggest velocities appear in the impeller vicinity, decreasing with the distance from the driving element, due to viscous damping of the fluid motion near the wall.

From the considered point of view, to obtain possibly general conclusions, it is useful to distinguish two categories of agitating systems:

-   open impeller (immersed in a tank, without a diffuser) (Fig. 1a);
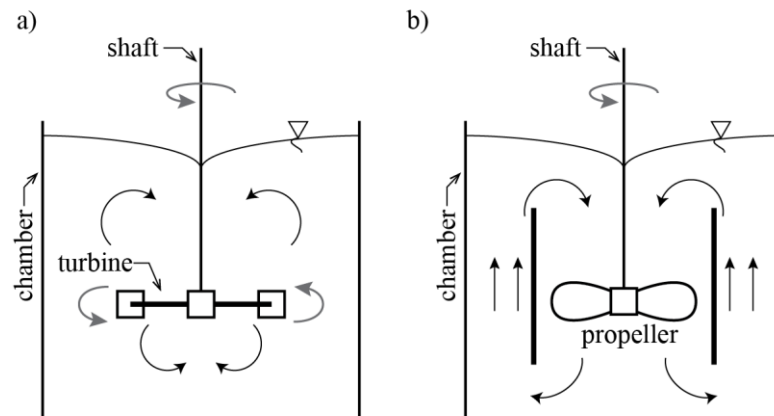-   impeller with a diffuser (Fig.1b).

Fig. 1. Velocity field structure for (a) open impeller (turbine) and (b) impeller with a straight diffuser.

In the first case (Fig. 1a), the velocity field is stated by the character of the impeller. As it was already mentioned, this motion will be some combination of the basic components – radial, tangential and axial. In the second case, in turn (Fig. 1b), which only regards those impellers that can induce an axial motion (pumping effect), the configuration of the velocity field mainly depends on the diffuser position. An important role will be played here by the motion parallel to the diffuser walls, combined with the intensive change of the flow direction near the inlet and outlet, together with the rotational motion eventually induced by the impeller.

These kinematic considerations on the functioning of agitators in blending systems were supplemented by experience resulting from investigations of vortex separators [9] and vortex flow controls [14], which gave the idea to enrich the circumferential component of motion (swirl). Generally, it is well known that this element of motion is of avail in the blending

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process. It acts to increase the turbulence, and in effect – intensifies the mass exchange, which is put to good use, for example, in some engines [17] and fluid-flow mixers. Such a solution can be found even in some very specific devices like micromixers applied in microelectromechanical systems [4].

The point is to find a diffuser shape which would generate an intensive motion in a blending chamber, without an excessive deformation of the free surface (i.e. with a limited air core, which appears during rotational liquid motion).

All these remarks allow a conclusion to be drawn that one could consider such a solution where the orientation of the inlet and the outlet from the pipe are different. A diffuser of such a shape should generate an intensive rotation around the chamber axis, superimposed with an axial flow along the vertical part of the diffuser. It appears that this combination, together with a radial motion, especially in the upper zone of the chamber, should give a sufficiently differentiated velocity field, so that one can expect a better blending intensity than in the case of the straight diffuser.

The schematic diagrams of the analyzed solutions are shown in Figs. 2 and 3. The idea described above can be put into effect in some different ways. Three variants, logical, evident and consistent with the general rules of hydrodynamics, were investigated in a laboratory:

- the twofold change of the diffuser direction in its lower part and the coaxial location of the impeller inside; tangent to the wall orientation of the outlet generates a horizontal circulation;

- one change of the diffuser direction ("single-elbow-diffuser", IV, Fig. 3a); the stream, striking the wall, divides into two parts, what should generate two horizontal vortices;

- division of the stream by a pipe-tee into two parts, oppositely directed ("double-elbow-diffuser", Variant V, Fig. 3b); each stream strikes the wall, which should generate four horizontal vortices.
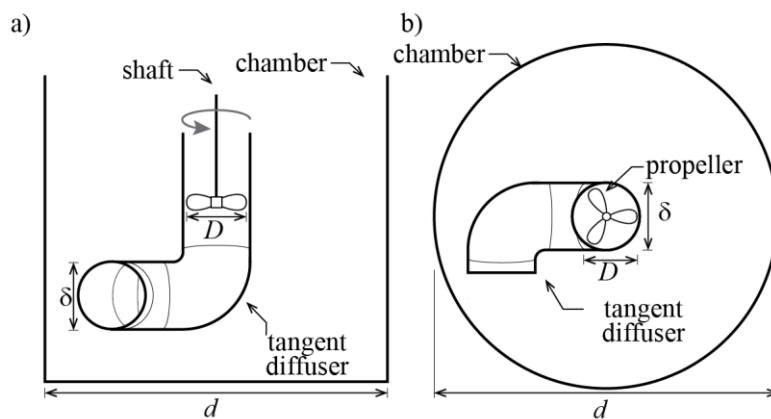

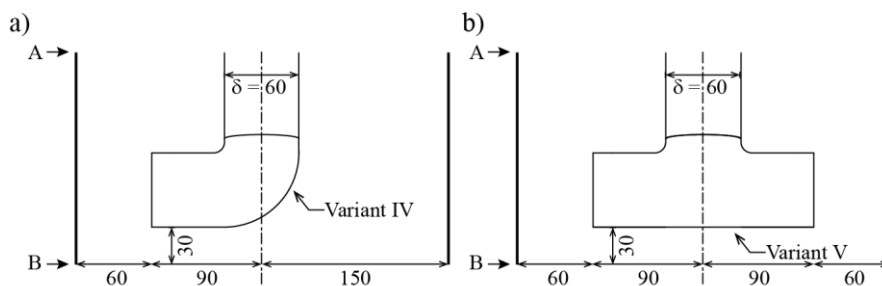Fig. 2. Tangent-diffuser idea (a – vertical section, b – plan view).

Fig. 3. Investigated variants IV (a – single-elbow-diffuser) and V (b – double-elbow-diffuser).

The dimensions provided in Figs. 3a,b correspond to the dimensions presented in Fig. 4., whereas capital letters A and B denote the cross sections positions between which the diffuser shape is different from the one presented in Fig. 4.

3. EXPERIMENTAL VERIFICATION

The test stand was made in Plexiglas, as a cylindrical upper chamber with a conical bottom part. Its shape and dimensions are shown in Fig. 4. An R50 agitator (CAT, Germany) with a propeller of diameter $D = 45$ mm was used as a mixer.
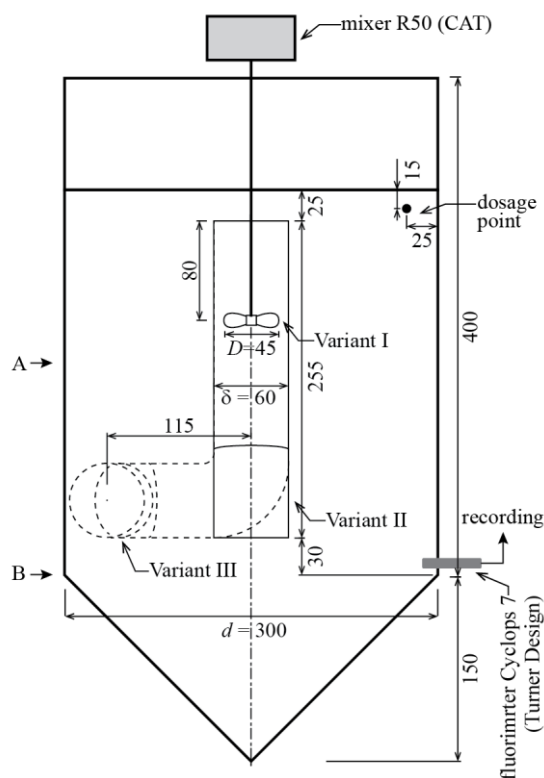
Fig. 4. Schematic diagram of the test stand and main dimensions in millimeters.

The measurements have been carried out for five variants of the blending chamber outfit:

Variant I – open propeller (Fig. 1a);

Variant II – propeller with a straight diffuser (diameter $\delta = 60$ mm, length 255 mm; Fig. 1b);

Variant III – propeller with a tangent-diffuser (Fig. 2a,b);

Variant IV – propeller with a single-elbow-diffuser (Fig. 3a);

Variant V – propeller with a double-elbow-diffuser (Fig. 3b).

The blending time t_B has been determined by means of the colorimetric method. In each test, the chamber was filled with pure water ($V = 25$ dm^3) and after the stabilization of the agitator speed, a dose of 1.5 ml Rhodamine WT (containing $M = 0.6$ mg of pure dye) was introduced instantaneously (for point of injection – see Fig. 4). The tracer concentration and its time variation $c(t)$ was measured and recorded with the Cyclops 7 fluorimeter (Turner Designs, USA), placed in the test point (see Fig. 4). Some examples of this function are shown in Fig. 5, where the plots of the concentration measurement during 120 s (for n equal 400 rpm, 800 rpm and 1200 rpm respectively) are displayed.
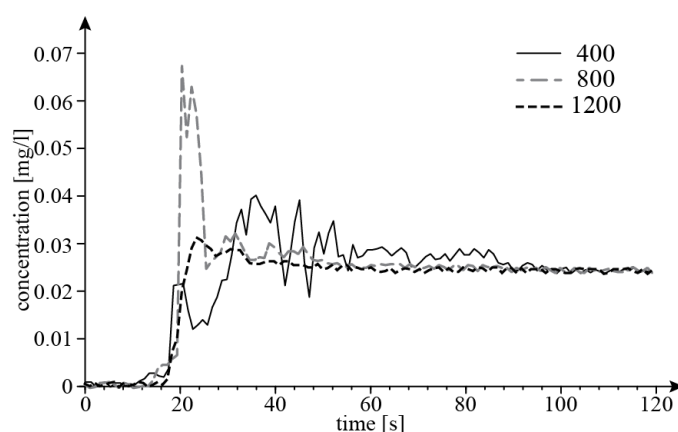

Fig. 5. Concentration-time dependence for variant IV.

The blending time was determined from each function $c(t)$ as the value after which the actual concentration differed from the terminal value $c_K = M/V$ not more than 2%:

$$0.98 < c(t_B) < 1.02 \, c_K. \tag{10}$$

During the experiments also the dependency between blending time and propellers rotational speed was investigated for each variant (I, II, III, IV and V). The plot showing such dependence is displayed in Fig. 6.

Together with the blending time and the tracer concentration, the power consumption by the propeller was also measured (Fig. 7). The vertical error bars present the standard error of the power measurement.
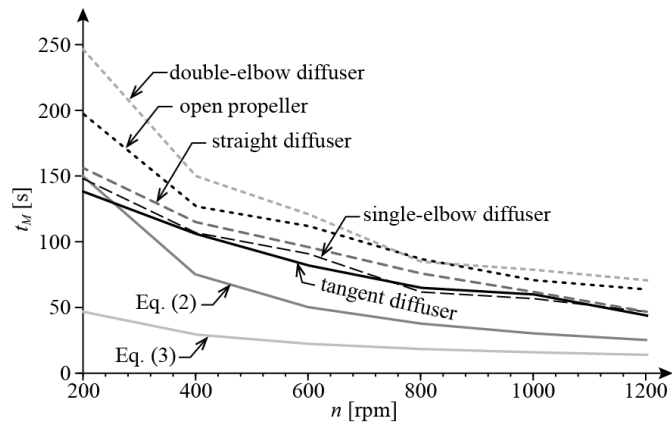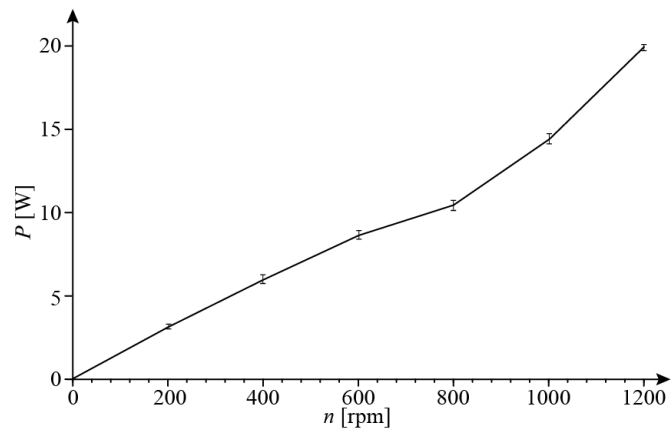
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Fig. 6. Blending time versus rotational speed.

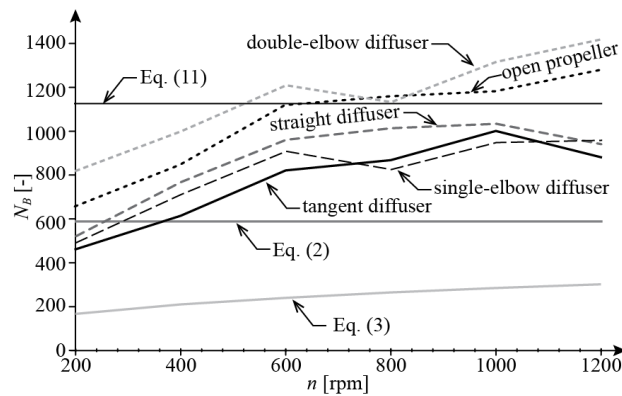Fig. 7. Power input versus rotational speed (with standard error bars).

Fig. 8. Dimensionless blending time versus rotational speed.

4. DISCUSSION AND CONCLUSIONS

The results of the investigations enable evaluation of the basic concept of the paper (i.e. the influence of the horizontal liquid rotation on the blending time). The answer is not univocal, although very strongly suggests that the blending process can be easily improved. The

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experiments showed that it is possible to increase the blending efficiency by modifying the velocity field in the batch reactor.

For the two of five investigated cases (namely variants III and IV) the blending time is shorter than for the open propeller and the straight diffuser. Distinctly worse effect is observed in the variant V, where the blending time elongates. Apparently it is a consequence of the stream division. In this case probably the flow energy is too low to generate horizontal vortices, expected theoretically. Decreasing flow velocity disrupts the mixing process because in place of expected vortices, local disturbances are generated, that worsen blending conditions.

Generally, the differences among the blending times for different variants are not very high. However the difference between the bending time for open propeller (Variant I) and variants II, III, and IV differ significantly, especially for low rotational speed. The variants including the diffusers performed better. This is important practical conclusion as it is strongly connected to the amount of energy required to perform the blending.

It should be noticed that the blending time obtained on the basis of the theory can differ significantly from the observed value. According to the simplified approach, its dimensionless form should be constant (Eq. 1). As it is seen in Fig. 8, this parameter increases with the rotational speed. This is worth saying that two relations cited in the paper (Eqs. 2, 3) give very different values of t_B. According to Eq. 2 the calculated blending time is comparable to the results of measurements, whereas Eq. 3 gives very low values of t_B.

Apparently different results brings Eq. 8, which for the investigated device ($D = 45$mm, $\delta = 60$ mm, $d = 300$ mm) takes the following form:

$$N_B = 1111.2. \tag{11}$$

The dimensionless blending time is here much closer to the measured values, especially for higher rotational velocities ($n > 600$ rpm). But it is a self-evident effect, as this relation, derived for the jet mixed tanks, much better goes with the discussed object, equipped with a diffuser.
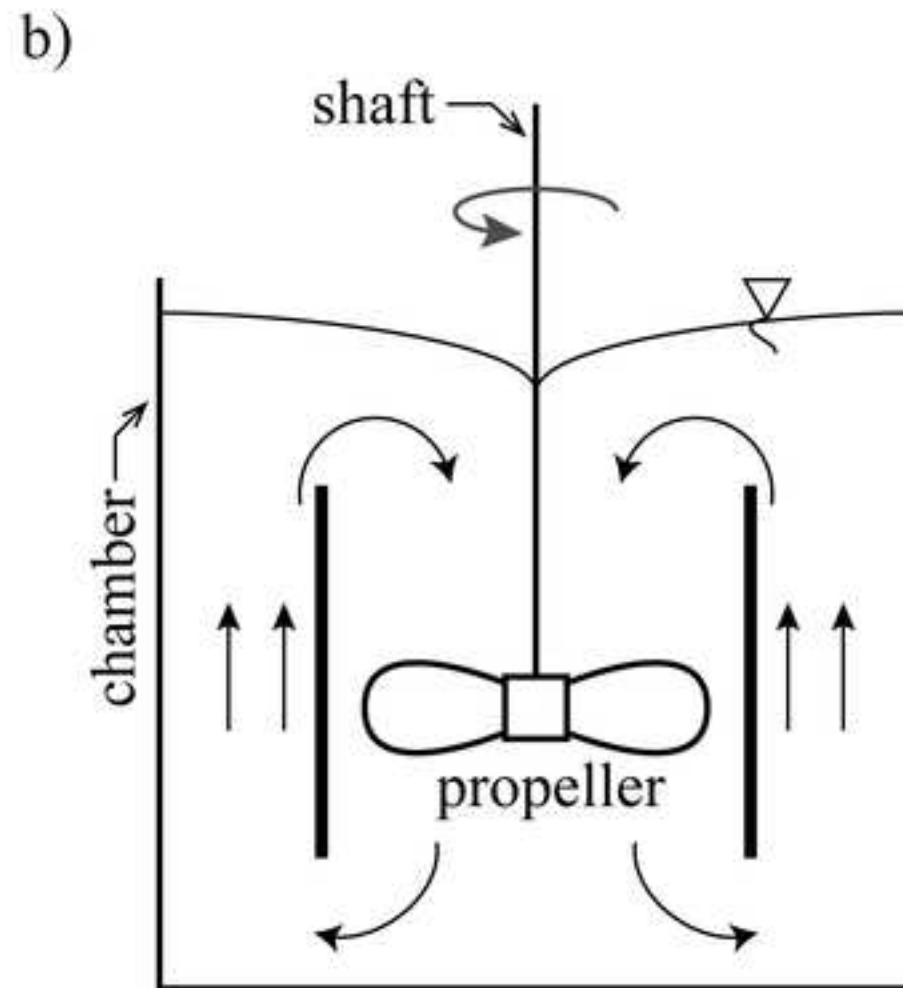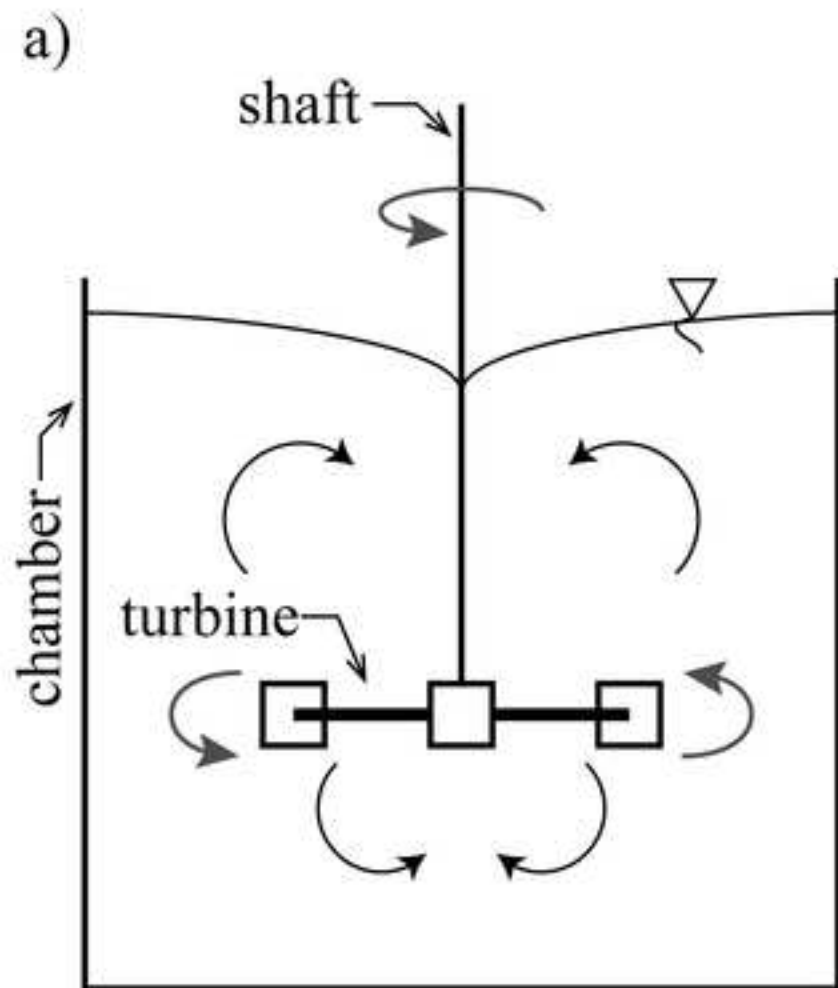
Concluding, one should say that the discussed solution doesn't change the blending effectivity radically, but has a positive influence on this process, assuming that the energy of stream leaving the diffuser is high enough to create the circulation. This information could be interesting for engineers designing the blending systems, as the blending efficiency increases the lower rotational speed of impellers can be used leading to significant energy savings in long term exploitation of the blending batch reactors.
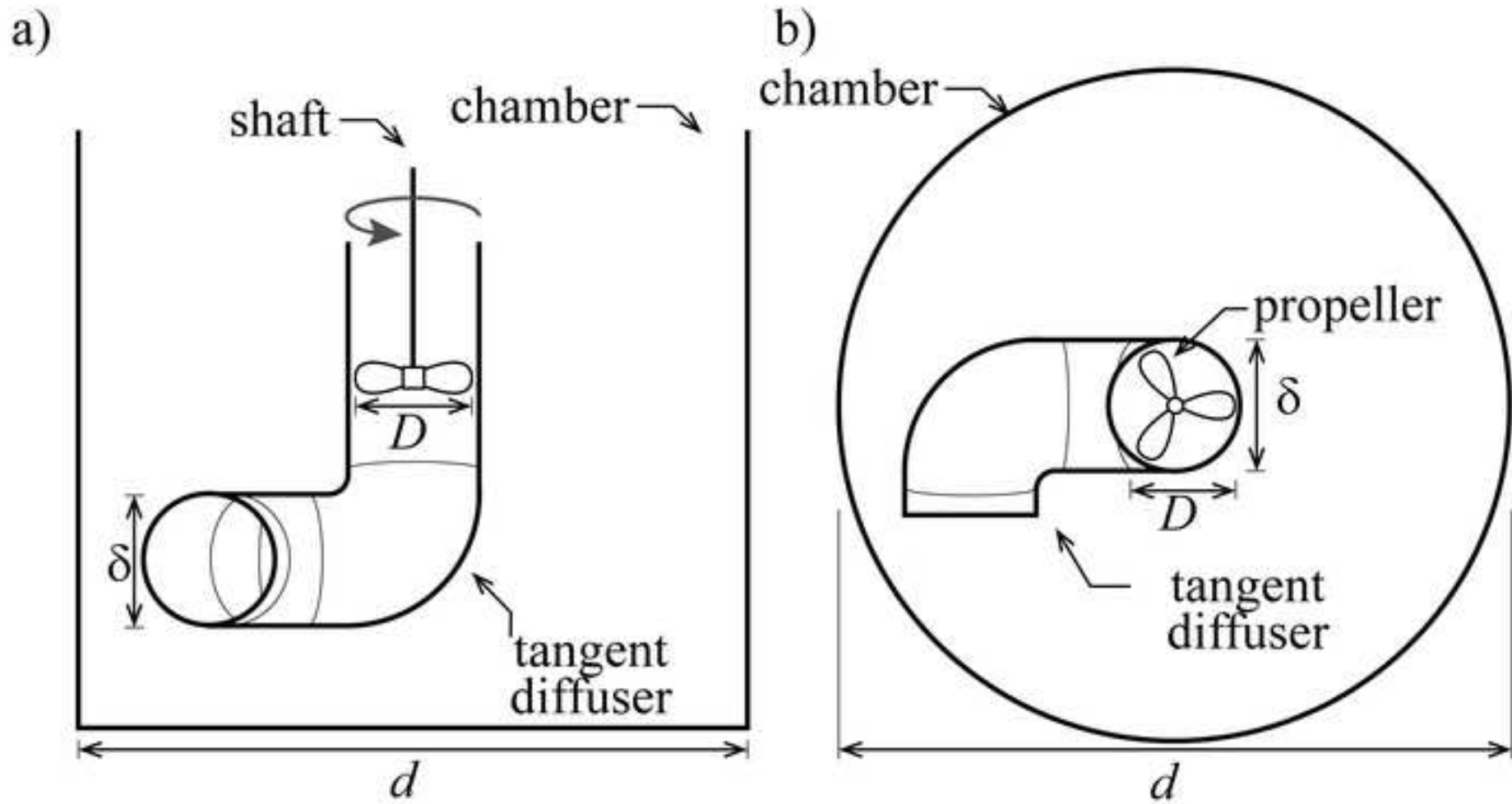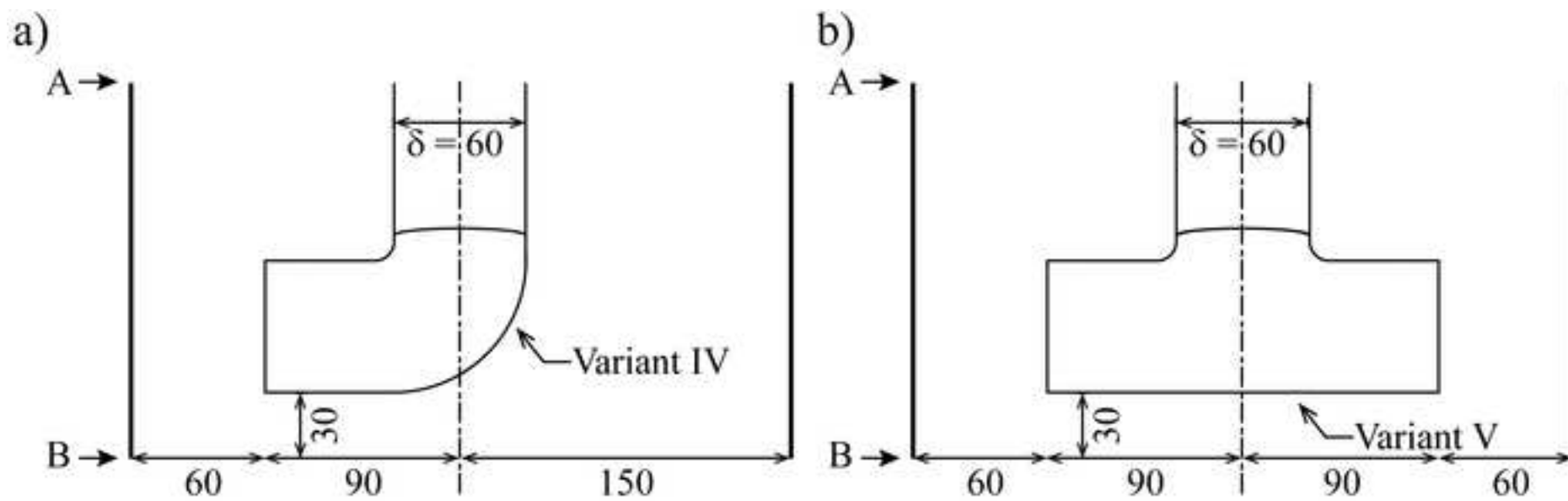
REFERENCES

[1] W. Artichowicz, J.M. Sawicki, Determination of mechanical energy loss in steady flow by means of dissipation power, *Archives for Hydro-Engineering and Environmental Mechanics* 2 (2017) pp.73-85.

[2] G. Ascanio, Mixing time in stirred vessels: A review of experimental techniques, *Chinese J. Chem. Eng.* 23 (2015) pp.1065-1076.

[3] A. Bakker, Blend times in stirred tanks, http://www.bakker.org.

[4] J.J. Chen, C.H. Chen, Investigation of swirling flows in mixing chambers, *Modelling and Simulation in Engineering* (2011) DOI 10.1155.2011/259401.

[5] J.B. Fasano, A. Bakker, W.R. Penney, Advanced impeller geometry boosts liquid agitation, *Chemical Engineering* (1994), No. 8

[6] A. Gandhi, S.O. Sen, D. Manna, C. Roy, K.K. Sen, S.D. Roy, Studies on the effect of mixing time, speed and concentration of one component on mixing index, *Indian Res. Journal of Pharmacy and Science* (2017), DOI 10.21276/irjps 2017.4.1.3.

[7] I.M. Gana, Influence of blending time on the efficiency and milk consistency of a grain drink processing, *Experimental Findings* (2013), DOI 10.13149/RG.2.1.2660. 3604.

[8] R.K. Grenville, J.N. Tilton, Jet mixing in tall tanks: Comparison of methods for predicting blend times, *Chem. Eng. Research and Design* (2011), DOI 10.1016/i.cherd 2011.05.014.

[9] M.A. Gronowska-Szneler, J.M. Sawicki, Simple design criteria and efficiency of hydrodynamic vortex separators, *Water Sci. Technol.* 70.2 (2014) pp.457-463.

[10] S. Hiraoka, R. Ito, Simple relationship between power input and mixing time in turbulent agitated vessel, *J. of Chem. Eng. of Japan* (1977), vol. 10, No. 1.

[11] S.M. Kvesta, D. Mao, V. Roussinova, Batch blend time in square stirred tanks, *Chem. Eng. Sci.* (2006) *61,* pp.2823-2825.

[12] I.H. Lehrer, Mixing time prediction, Proc. of 8th Australasian Fluid Mechanics Conf. (1983) Newcastle (NSW) 8A1-8A4.

[13] T. Maruyama, Y. Ban, T. Mizushina, Jet mixing of fluids in tanks, *J. of Chem. Eng. of Japan* (1982), vol. 15, No. 5, pp. 342-348.

[14] S. Mielczarek, J.M. Sawicki, Determination of mechanical energy loss in steady flow by means of dissipation power, *Arch. Hydro-Eng. Environ. Mech.* 2 (2017) pp.73-85.

[15] M. Moo-Young, K. Tickar, F.A.I. Dullien, The blending efficiencies of some impellers in batch mixing, *AIChE* 18 (1972) pp.178-182.
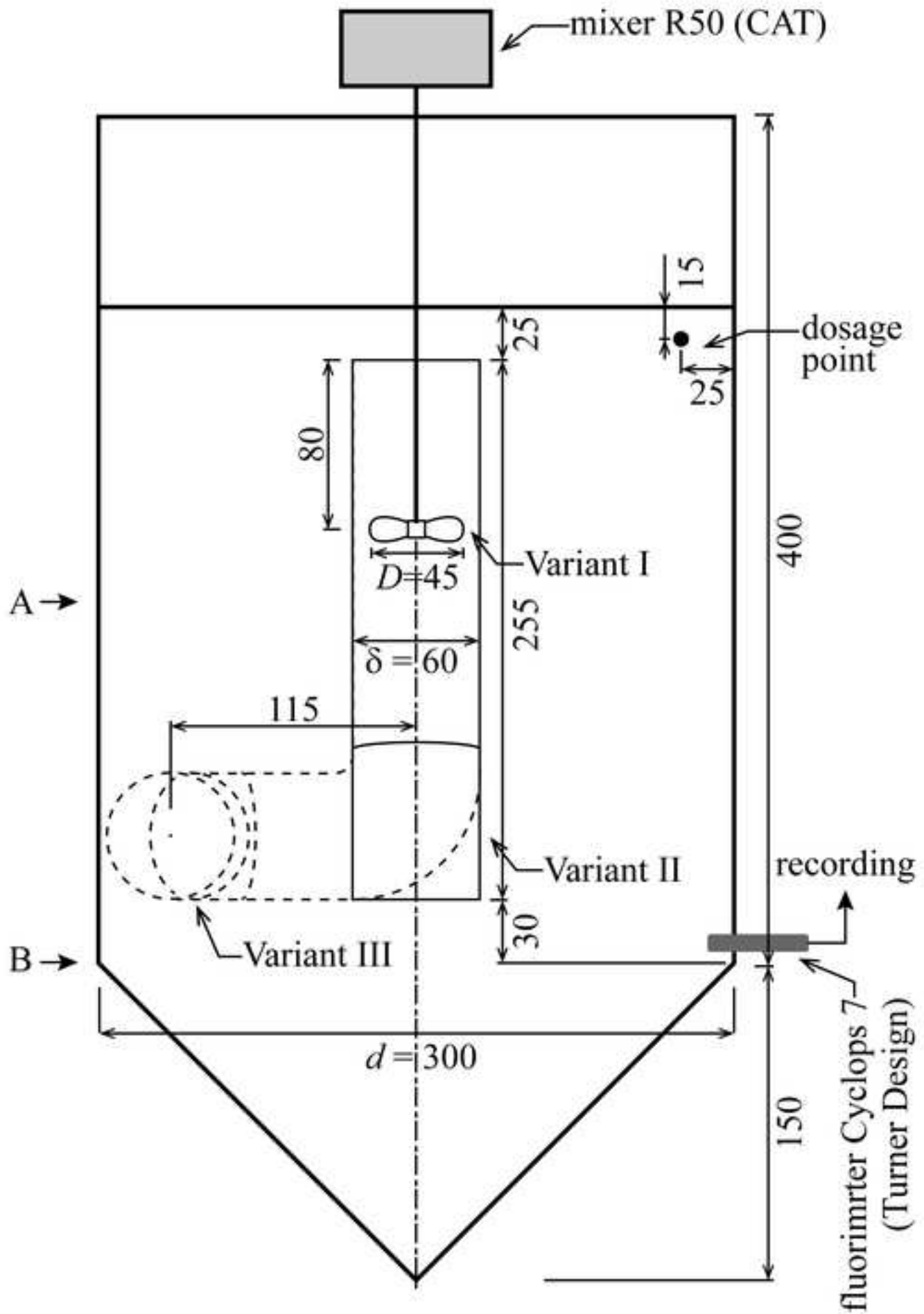
[16] S. Nagata, Mixing. Principles and applications. Halsted Press, New York 1975.

[17] A. Rubel, Some effects of swirl on turbulent mixing and combustion, NASA Report CR-1956 (1972) Washington DC.

[18] J.M. Sawicki, M.K. Skuza, S. Bering, Tracer investigations of dynamic properties of fluid-flow reactors, *Water Management and Hydraulic Engineering (Proc.),* Slovak University of Technology, Bratislava (Slovakia) 2003.

[19] J.C. Slattery, Advanced transport phenomena, University Press, Cambridge UK 1999.

[20] B. Valeur, M.N. Berberan-Santos, Molecular fluorescence. Principles and applications. Wiley-VCH Verlag, Berlin 2013.

[21] P. Zima, J. Mąkinia, M. Swinarski, K. Czerwionka, Effects of different hydraulic models on predicting longitudinal profiles of reactive pollutants in activated sludge reactors, *Wat. Sci. Tech.* Vol. 58 (2008) No.3 pp. 555-561.

[22] M. Zlokarnik, Eignung von Ruehrern zum Homogenisieren von Fluessigkeitsgemischen, *Chem Ing. Techn.* 39 (1967) pp.539-548.
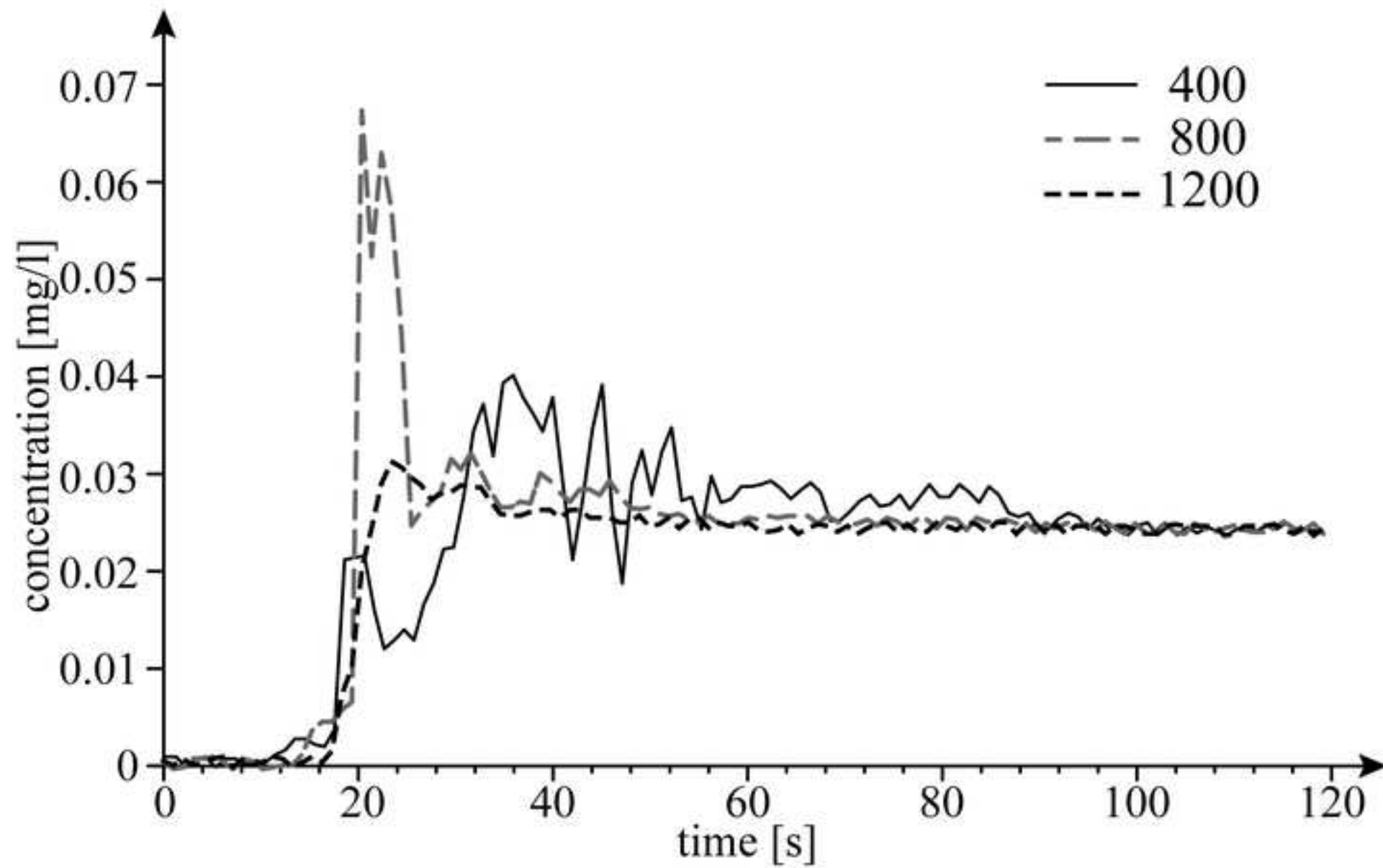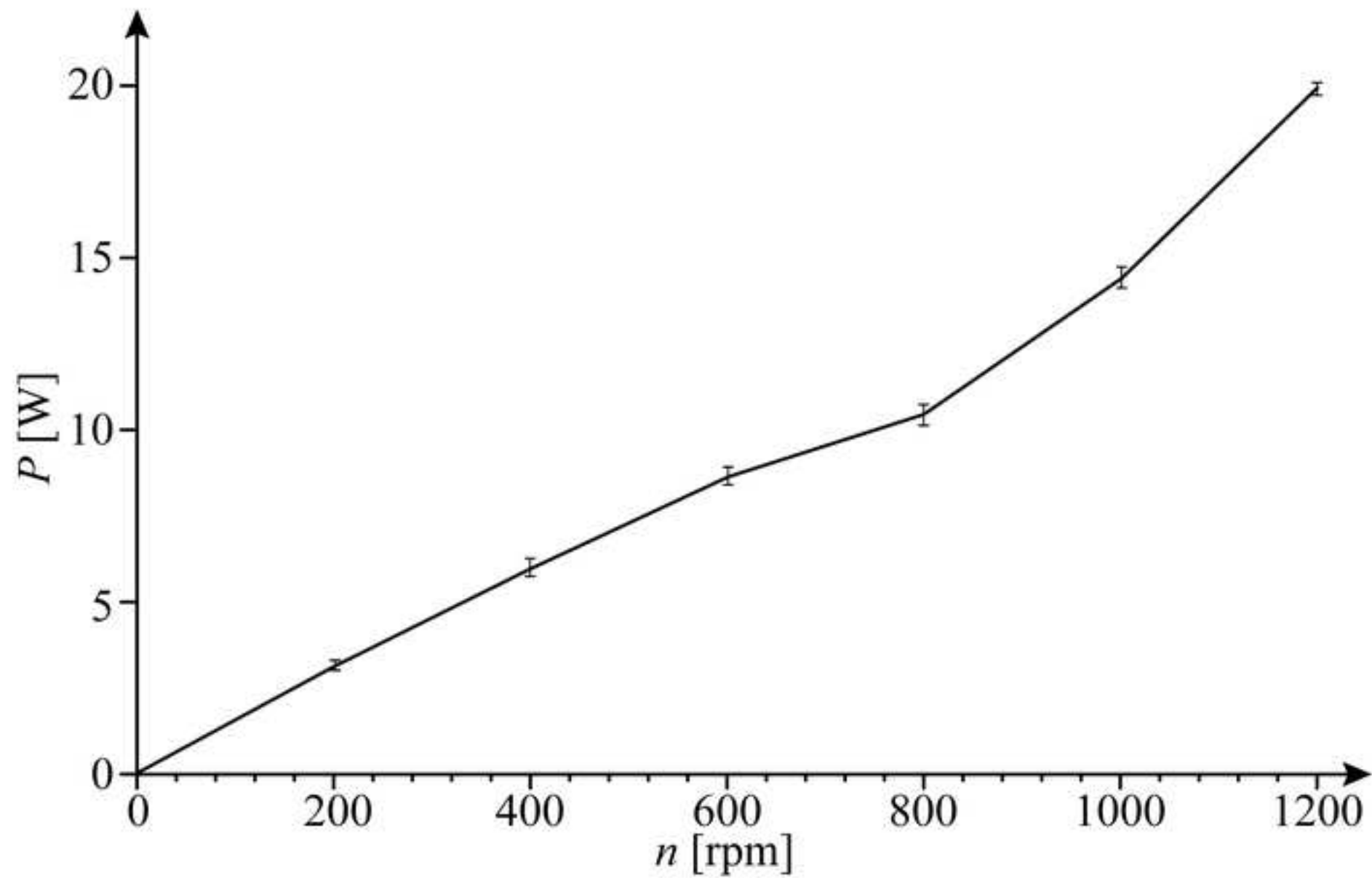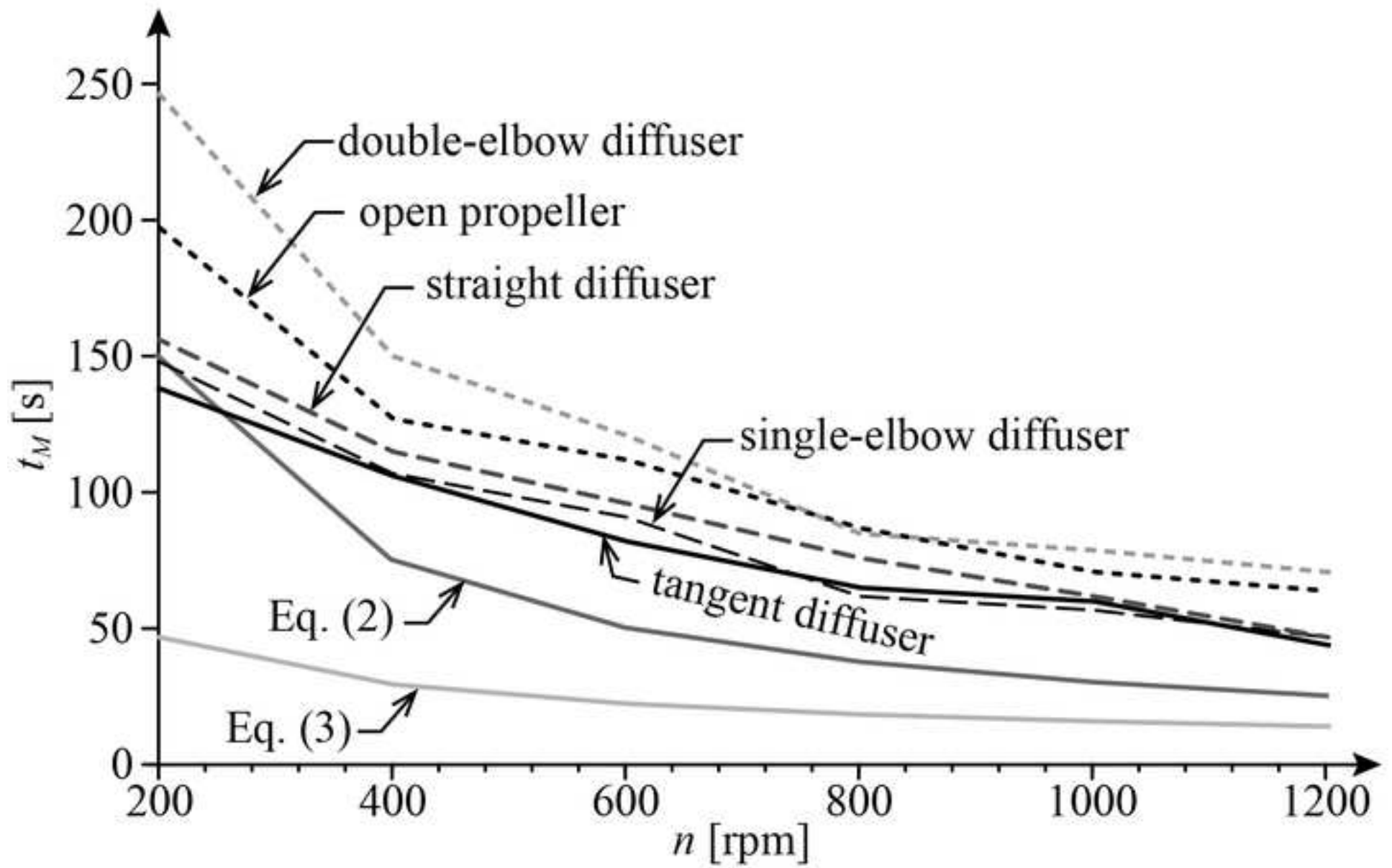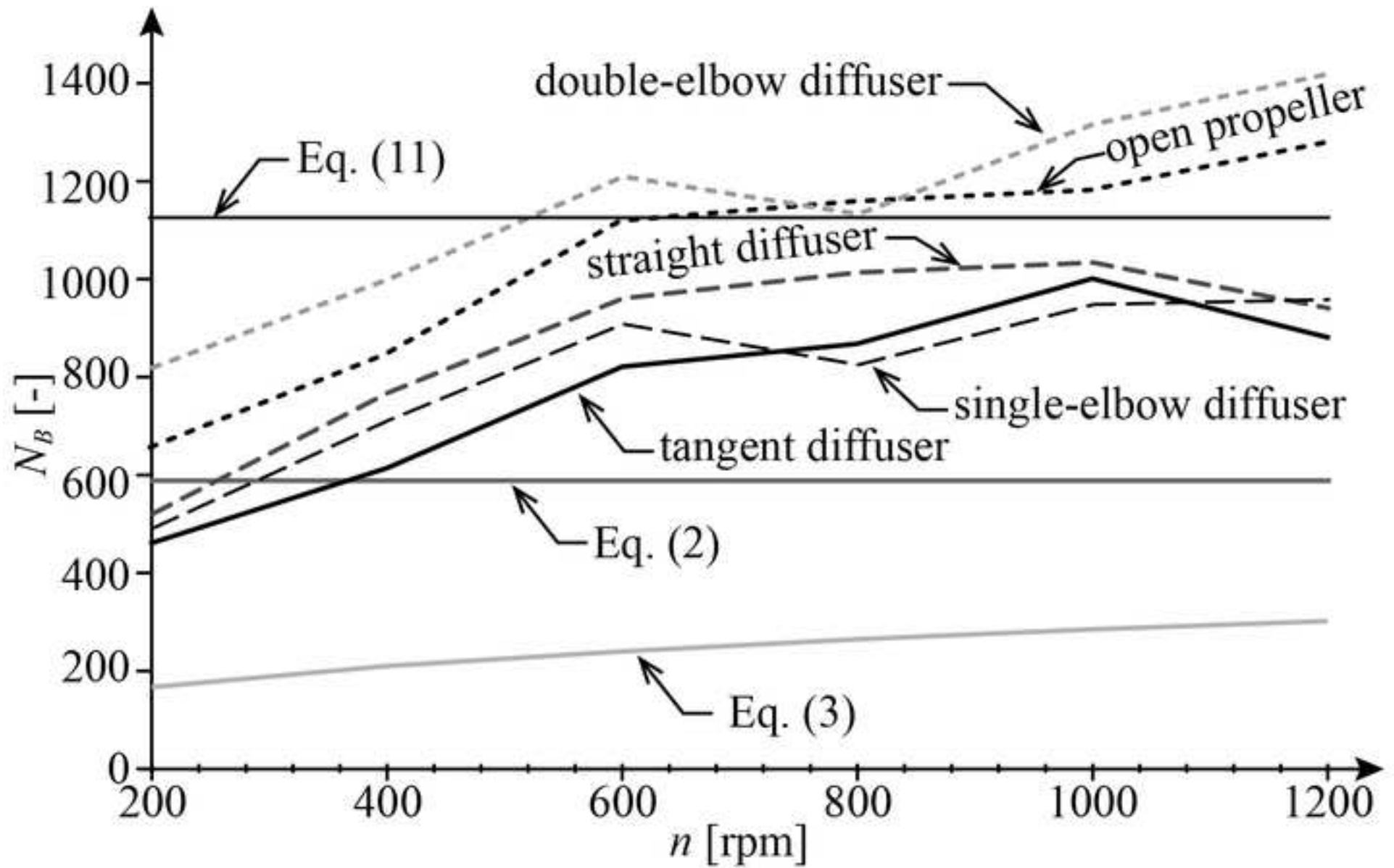
Fig 1

Fig 2   Click here to access/download;Figure;Figs_2.tif ±

a)

b)

Fig 3   Click here to access/download;Figure;Figs_3.tif ±

Fig 4

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mixer R50 (CAT)

dosage point

Variant I

$D = 45$

$\delta = 60$

115

Variant II

Variant III

$d = 300$

recording

fluorimrter Cyclops 7 (Turner Design)

15

25

25

80

255

400

30

150

Fig 5

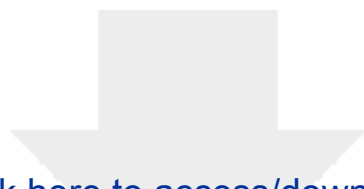Fig 7

Fig 6 (updated)

Fig 8 (updated)

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