Performance Enhancement of Machines with Helical Elements

COSMIN V. JINESCU*

Politehnica University of Bucharest, Department of Industrial Process Equipment, 313 Splaiul Independentei, Bucharest, Romania

A number of machines with helical active elements used in the process industries are analyzed: helix and turbine impellers with draft tubes; screw of a single screw extruder and helical flight feeders. These have in common the helical shape and functioning with a fully filled section with transported liquid or material. Based on the analysis of the movement of the liquid or granular material determined by the helical surface, the following relationships are established: pumping flow rate for helix impellers; transport flow rate of an extruder screw and of a screw conveyor functioning with a fully filled section with material. The relationships evidenced the importance of a correct choice for the inclination angle of the helical flight and the influence of friction between liquid or granular material and the helical surface.

Keywords: output; screw machines; impeller; helical elements; friction coefficient

Active elements with helix surface or deriving from a helix surface are used in numerous machines from process industries (chemical, petrochemical, food, polymer and rubber processing, ceramics, textiles, cellulose and paper), for transport of powdery and granular materials.

The active elements of machines from process industries evolved along with the development of new production technologies. It is noticeable the improvement of helixes and helical conveyors of machines used in mixing processes, screw centrifuge rotors, screw compressor rotors, screw pump rotors, polymer processing machines, helical conveyors and elevators, helical feeders [1].

From a functional point of view one can notice the following cases:
- machines in which the volume offered by the shape or the helical channel is:
- partially occupied by the processed material or transported (some helical conveyors, twin screw extrusion machines in the feeding zone); - totally occupied by the processed material, with the development of a certain pressure during movement;
- processed/ transported material has along the entire length of the movement direction: - almost constant temperature; - variable temperature, generally increasing from the machine inlet to outlet.

The flow rate of machines with active helical elements depends on the degree of helical channel occupancy, on the evolution of temperature and pressure of the processed/ transported material.

In the case of helical conveyors with partially occupied channel section with granular of powdery material or for twin screw extruders, the flow rate is proportional with the filling coefficient of the channel transversal section, ensured by a variable flow rate feeder.

For screw machines with fully filled channel transversal section with transported material since the feeding zone, the flow rate is determined by the interaction between the fed material and the surfaces with which it comes into contact, by means of the friction coefficients between the transported material and these surfaces.

The paper analyses the influence of the friction coefficient between the transported material and the helical elements metallic surfaces, in the following cases:

-helix of a mixing impeller system in a draft tube (fig. 1);
-screw of a single screw extruder for polymer, rubber or ceramic materials processing (fig.2);
-shaft with helical flights used in the transport of solid materials or as a feeder (fig. 10).

Flow rate of a helix type impeller in a draft tube

Generally, draft tubes are used together with the following impeller types: helix (fig. 1), turbine (fig. 3) or screw (fig. 4). The draft tube allows the ordering of the liquid flow inside the vessel (fig. 1). It is thus ensured the continuous circulation of the entire liquid quantity through the helix zone of maximum mixing intensity. It is assured the circulation, turbulence and mixing of the components introduced inside the vessel. The formation of a central vortex is therefore avoided for liquids with relatively low viscosity.

Helix type impeller (fig. 1) creates an axial flow pattern, for which reason a single draft tube is sufficient. The helix can be mounted at the entry, inside or at the exit of the draft tube. The turbine impeller (fig. 3) creates a radial flow pattern. Liquid admission is axially therefore two draft tubes are required. The screw type impeller, used for high and very high viscosity materials, can be fitted with a single draft tube (fig. 4).
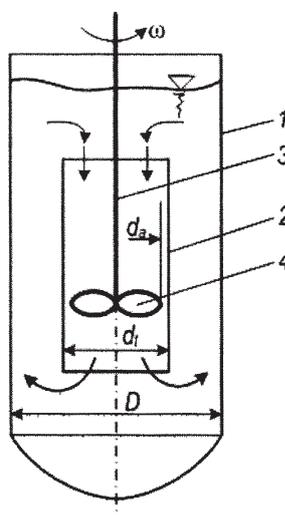

Fig.1. Vessel with impeller for mixing of liquids: 1 – vessel; 2 - draft tube; 3 - shaft; 4 - helix

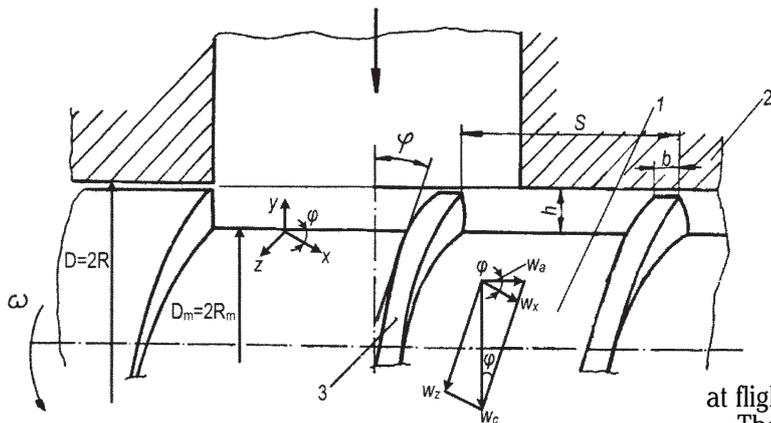** email: cosmin.jinescu@yahoo.com; Tel. 021.4029193*

Fig. 2. Section through the screw (1) inside the barrel (2). Screw has a helical flight (3) with an inclination angle φ (at flight tip) to the diameter of screw.
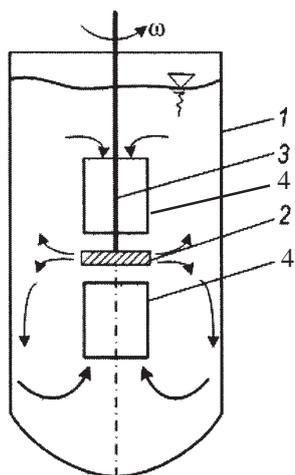

Fig.3. Vessel (1) with turbine impeller (2) on a shaft (3) in a functional unit with draft tubes (4)
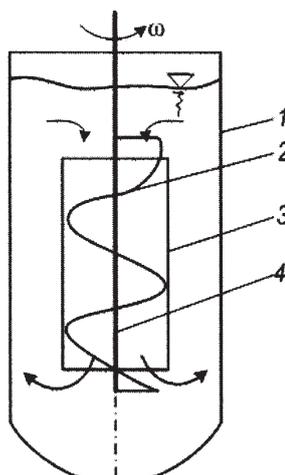
Fig. 4. Vessel (1) with helical impeller (2) on a shaft (4) in a functional unit with draft tube (3)

Specific conditions for helix impellers characterized by a relatively high pumping capacity are analyzed. The helix is part of a helical surface with an inclination angle φ (fig. 5). Helix pitch to the impeller diameter d_a (fig. 1) is given by:

$$S = \pi d_o tg\varphi \qquad (1)$$

The liquid is pushed by helix surface perpendicular to flight side advancing:
- without friction, over the length $\overline{BC_1}$. At a complete rotation, the liquid advances axially over the distance $S_o = \overline{BC_1} \cos \varphi = S \cos^2 \varphi$ – at flight tip and over distance $S_{ob} = S \cos^2 \varphi_b$ - at flight bottom, where φ_b is the flight inclination angle to helix axis,

$$tg \; \varphi_b = \frac{S}{\pi d_b} \qquad (2)$$

where d_b is the flight diameter;
- due to friction between liquid and the helix surface, liquid moves in reality over the distance BC_1 under friction angle α (fig. 5), defined by relationship $\alpha = arctan f$, where f is the friction coefficient between the liquid and helix blade surface.
The axial movement for a complete rotation of the helix is

$$S_0' = \frac{\overline{BC_1}}{\cos \alpha} \cdot \cos(\varphi + \alpha) = \frac{S \cdot \cos \varphi}{\cos \alpha} \cdot \cos(\varphi + \alpha) \qquad (3)$$

at the tip of the helix;

$$S_{0b}' = \frac{S \cdot \cos \varphi_b}{\cos \alpha} \cdot \cos(\varphi_b + \alpha) \qquad (3')$$

at flight bottom.
The helix surface between diameters d_a and d_b (fig. 6) can be considered being formed from a multitude of helical lines, each with a different inclination, comprised between φ and φ_b. However, flow rate create only those segments of the helix surface with inclination angles between φ and $90° - \alpha$. For helix diameters $d \leq d_o$, where d_o corresponds to an inclination angle of $90° - \alpha$, the liquid rotates, but does not move axially, with no contribution to the flow rate. Diameter d_o is given by relationship

$$d_o = \frac{S}{\cos \alpha} \qquad (4)$$

It results the following practical recommendation: diameter of the helix impeller shaft must be greater than d_o,

$$d_b > d_o \qquad (5)$$

The volumetric flow rate produced by an impeller is given by relationship

$$G_v = A_a w_{med} \qquad (6)$$

where A_a is the surface of the section "covered" by the impeller. $A_a = k_o \frac{\pi d_a^2}{4}$ where $k_o = 0.8$ is the liquid flux contraction coefficient; generally, $k_o = 0.8$. By example, (fig. 1) the average liquid speed in this case is its helix produced axial speed

$$w_{med} = k_w w_a \qquad (7)$$

where w_a is the ideal axial speed and k_w is a velocity coefficient that takes into account the liquid slip versus the helix surface (k_{w1}) and the velocity profile (k_{w2}) between radius $0.5 \; d_b$ and $0.5 \; d_a$. Thus the velocity coefficient expression [5]

$$k_w = k_{w1} k_{w2} \qquad (8)$$

The slipping coefficient represents the ratio between the axial distance covered by the liquid and the length of a pitch (fig. 5). At shaft surface, at radius $0.5 \; db$, the following relationships are used for k_{w1} calculation, in the case of movement without friction and for movement with friction, respectively.

$$k_{w1} = \frac{S_{0b}}{S} = \cos^2 \varphi_b$$

$$k_{w1} = \frac{S_{0b}'}{S} = \frac{\cos \varphi_b}{\cos \alpha} \cdot \cos(\varphi_b + \alpha) \qquad (9)$$

The values for friction coefficient k_{w1} fall between 0.7 and 0.8, with some values determined experimentally at 0.76 [3].

The velocity averaging coefficient k_{w2} represents the ratio between liquid average velocity, w_{med}, in the range $0.5d_b - 0.5d_a$, and the speed at shaft surface, w_b,

$$k_{w2} = \frac{w_{med}}{w_b}$$

Average speed of the material, $w_{med} \sim S_o'(d_m)$, and speed at the shaft surface $w_b \sim S_o'(d_b)$, with

$$S_0'(d_m) = 0.5(S_0' + S_0'(d_b)) \qquad (10)$$

where S_o' is the pitch at helix tip (d_a). It results for k_{w2} the following relationship:

$$k_{w2} = \frac{1}{2}\left[1 + \frac{\cos\varphi \cdot \cos(\varphi + \alpha)}{\cos\varphi_b \cdot \cos(\varphi_b + \alpha)}\right] \qquad (11)$$

In the analysis above it was considered the same value for the friction coefficient between liquid and the helix over its entire surface. If friction is neglected, then $\alpha = 0$, so that

$$k_{w2} = \frac{1}{2}\left[1 + \frac{\cos^2\varphi}{\cos^2\varphi_b}\right] \qquad (12)$$

The liquid axial velocity

$$w_a = k_w \cdot n \cdot S_0'(d_m) \qquad (13)$$

where $S_o'(d_m)$ is given by relationship (10) and n is measured in *rot/s*. From relationships (3), (10) and (13) result the expression of liquid axial velocity determined by the helix rotating with rotational frequency n,

$$w_a = \frac{k_w \cdot n}{2} \cdot \frac{S}{\cos\alpha} \cdot [\cos\varphi \cdot \cos(\varphi + \alpha) + \cos\varphi_b \cdot \cos(\varphi_b + \alpha)] \qquad (14)$$

All the above considerations refer to the flow initiation zone, in the helix plane. For recipients without a draft tube, the helix generates a main stream which thins as it moves farther from the helix and entrains liquid through its frontier [2].

With $A_a = k_o(\pi d_a^2 / 4)$, from relationships (6) and (14) one obtains the following relationship for the helix pumped volumetric flow rate,

$$G_m = \frac{\pi}{8} \cdot \frac{k_w \cdot n \cdot S \cdot d_a^2}{\cos\alpha} \cdot [\cos\varphi \cdot \cos(\varphi + \alpha) + \cos\varphi_b \cdot \cos(\varphi_b + \alpha)] \qquad (15)$$

If the condition that the liquid in the vessel must pass a number of k times through the draft tube in a time unit is imposed, then the average axial velocity has the expression:
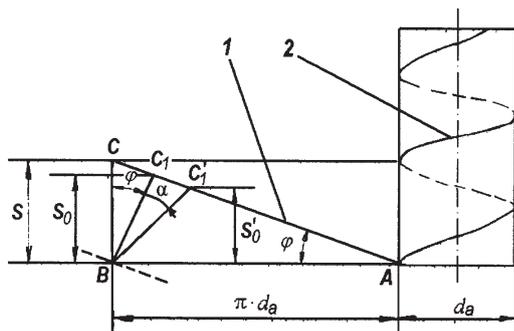

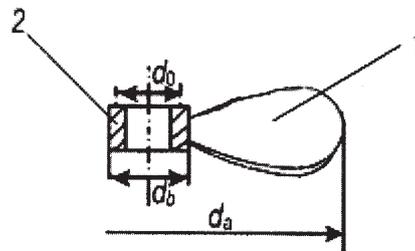Fig. 5. Projection (1) of the helical flight (2) over a pitch length (S)

Fig.6. Helix blades (1) extended between diameters d_a and diameter d_b of the shaft bolt (2).
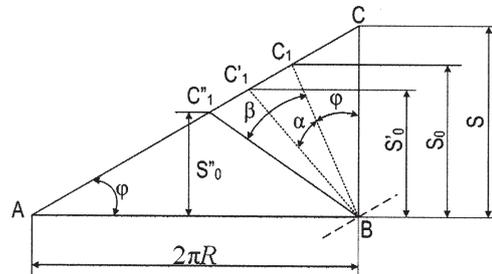

Fig.7. Material movement (BC_1'') with friction and counter pressure.

$$w_a = k \cdot \frac{V}{A} \qquad (16)$$

where V is the liquid volume in the vessel. For example, in the case of helix impellers, the parameter $k = 6-8$ passes per minute, for a liquid volume V of $0.25-10 \ m^3$ in a vessel without a draft tube and $k = 2-4$ passes per minute for $V = 1.6-16.6 \ m^3$ in vessels with draft tube.

From relationships (14) and (16) results the required helix rotational frequency

$$n = \frac{2k}{k_w} \cdot \frac{\cos\alpha}{S} \cdot \frac{V}{A} \cdot [\cos\varphi \cdot \cos(\varphi + \alpha) + \cos\varphi_b \cdot \cos(\varphi_b + \alpha)] \qquad (17)$$

For example, $\varphi = 25^\circ - 45^\circ$. Practically, in general, for helix impellers, $n = 100$-1500 rot/min. For foaming liquids, for example, $n = 150$-500 rot/min.

Flow rate generated by a screw in the feeding zone

The machines whose active element is a screw with helical channel with pitch S and channel depth h (fig. 2), can function with a totally filled or partially filled channel section with granular or powdery material. The case for a totally filled channel section with granular or powdery material is analyzed. When the material moves, in this specific case, generally, pressure increases along traveled length, and counter pressure must be taken into account. Therefore, the material pushed by the flight reaches the flight tip, at radius R, in point C_1'' instead of C_1' (fig. 7), under angle $\beta > \alpha$. Trajectory deviation versus BC_1' is greater than without counter pressure: $C_1C_1'' > C_1C_1'$. At screw surface level, at radius R_m things are happening the same, only here the circumferential length is $2\pi R_m$ instead of $2\pi R$ at flight tip. Thus,

$$\left.\begin{array}{l} tg\varphi = \dfrac{S}{2\pi R}; \\[2mm] tg\varphi_m = \dfrac{S}{2\pi R_m} \end{array}\right\} \qquad (18)$$

Because $R_m < R$ results that $\varphi_m > \varphi$ (fig. 8). It can be noticed that the axial movement of material at screw surface is lesser than at flight tip,

$$S_m'' < S_o'',$$

which shows that the axial speed is variable.

The point of zero axial displacement of the material is situated on the circumference of radius R_o given by the following relationship

$$R_0 = \frac{S tg\alpha}{2\pi} \qquad\qquad \text{at flight tip}$$

and

$$R_{0m} = \frac{S tg\beta}{2\pi} \qquad\qquad \text{at screw surface}$$

Because $\beta > \alpha$ results that $R_{o,m} > R_o$. At relatively high pressures it is possible that $R_{o,m} > R_m$. The material found between radii R_m and $R_{o,m}$ does not move axially and thus does not generate flow rate. The flow rate generated by the screw feeding zone is calculated with relationship (6), where the average axial velocity of the material is given by relationship (7) (fig. 2) and where the ideal axial velocity at core screw surface ($R_m = R-h$) has the expression

$$w_a = w_s \cos\varphi_m = w_c \sin\varphi_m \cos\varphi_m$$

where
$$tg\varphi_m = \frac{S}{\pi(D-2h)}$$

Because the velocity in the screw diameter plane, at screw core surface level is

$$w_c = \frac{(D-2h)}{2}\omega$$

where $\omega = \pi n / 30$ is the angular velocity and n – screw rotational frequency in $rot./min.$, results

$$w_a = 0.25(D-2h) \cdot w \cdot \sin 2\varphi_m \qquad (19)$$

Area of screw channel transversal section has the expression:

$$A = \pi(D-h)\cdot h - i_p \cdot \frac{h\cdot b}{\sin\overline{\varphi}} \qquad (20)$$

where i_p is the number of beginnings of the helical flight, b - flight width on axial direction;
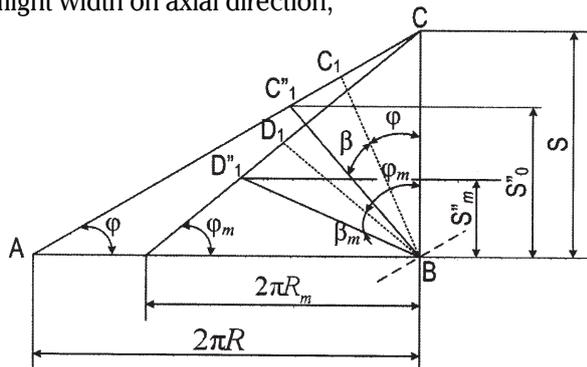

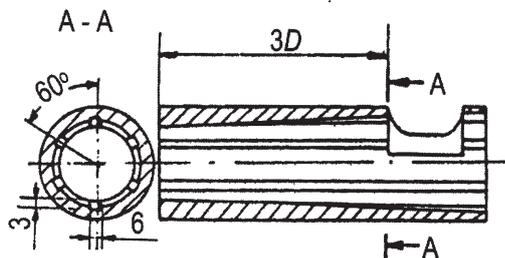Fig. 8. Material movement at helical flight tip (BC_1'') and at screw surface (BD_1'')

Fig. 9. Axial grooves in the feeding zone of a single screw extruder.

$$\overline{\varphi} = arctan\frac{S}{\pi(D-h)} \text{ - flight inclination angle in the middle}$$
of channel depth.

The screw generated volumetric flow rate has the expression [4]

$$G_v = 0.25\pi \cdot k_w \cdot h \cdot (D-h)\cdot (D-2h)\cdot E_s \cdot \omega \cdot \sin 2\overline{\varphi} \qquad (21)$$

where

$$E_s = 1 - \frac{i_p \cdot b}{\pi \cdot (D-h)\cdot \sin 2\overline{\varphi}}\quad \bullet$$

The parameter k_w is calculated with relationship (8) where k_{w1} results from the second relationship (9) and k_{w2} is calculated with relationship (11) if the friction coefficient between the material and the screw core, α_m (at radius R_m), is equal to the friction coefficient between the material and the upper part of screw flight, α_s (at radius R), case when $\alpha = \alpha_m = \alpha_s$. Contrary, the relationship (22) [4] is used

$$k_{w2} = 0.5 \cdot \left[1 + \frac{\cos\varphi \cdot \cos(\varphi+\alpha)}{\cos\varphi_b \cdot \cos(\varphi_b+\alpha)} \cdot \frac{\cos\alpha_m}{\cos\alpha}\right] \qquad (22)$$

For $\alpha = \alpha_m$, from the above relationship results expression (11) for k_{w2}.

For a given screw geometry (D; h; b; i_p; φ) and a given rotational frequency (n), flow rate can be increased only through the increase of parameter k_w [7-9]. For a granular material to be transported, one needs to ensure its movement close to the axial direction of screw (along S), instead of moving along BC_1'' and BD_1'', respectively (fig. 8). This is achieved by a feeding zone with 4 axial grooves (fig. 9) [5; 6].

Analysis of screw feeders

Screw feeders are used when feed from a slotted bin outlet is required. Screw feeders are built by welding one or more helical flights onto a shaft (fig. 10). The feeder with constant pitch and constant diameter (fig. 10, a) withdraws material from the upper end of the bin causing the remaining material to stagnate.
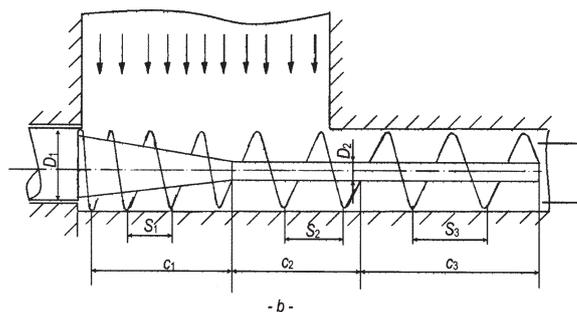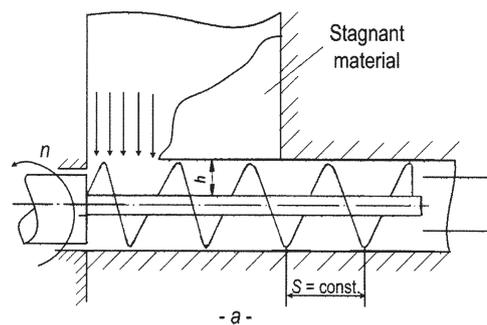

Fig. 10. Screw feeders: a – with constant diameter pitch (S=constant); b – with variable diameter (D_1; D_2) and pitch (S_1; S_2; S_3).

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The feeder with conical shaft and half-pitch section (c_1), increasing pitch section (c_2) and a conveying section (c_3), maintains uniform mass flow (fig. 10,b) because the discharge capacity increases in the direction of discharge [5].

Generally, the initial part of the feeder is filled with granular or powdery materials, its calculation being made using relationships established for screw machines.

Conclusions

From the multitude of helical element used as active parts for machines in process industries, the paper analyses the helix impellers, extruder screws and helical flight feeders.

Flow rate relationships were evidenced for these helical elements which are similar from the functional point of view.

The influence of the inclination angle of the helical flight and of the friction coefficient between the helical flight and the transported material or the pumped liquid was analyzed.

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