Korean J. Chem. Eng., 32(1), 37-42 (2015)
DOI: 10.1007/s11814-014-0180-6

pISSN: 0256-1115
eISSN: 1975-7220

Energy consumption of the flow in pulsed extraction columns with internals of discs and rings (doughnuts)

George Angelov*,† and Christophe Gourdon**

*Institute of Chemical Engineering, Bulgarian Academy of Sciences, Sofia, Bulgaria
**Laboratory of Chemical Engineering, CNRS, Toulouse, France
(*Received 20 March 2014 • accepted 27 June 2014*)

Abstract−This paper deals with determination of energy consumption due to pressure drop in pulsed extraction columns with internals of discs and rings (doughnuts). While the common approach assumes equality of a pulsed flow with a given mean velocity to a permanent flow with the same velocity, here the periodical flow velocity pattern is taken into consideration. It is shown that the energy consumption in case of a pulsed flow is different and quite larger than that of an "equivalent" permanent flow, and should be accounted for the sake of a more precise column design. A correlation for determination of energy consumption in case of sinusoidal periodic pulsed flow is proposed, which reflects the influence of mean flow velocity and geometry parameters (plate free area and interplate distance). Its reliability is checked by comparison of calculated results and experimental data.

Keywords: Discs and Rings (Doughnuts) Column, Pulsed Flow, Energy Consumption, Pressure Drop

INTRODUCTION

The total energy consumed when running an apparatus is a sum of a number of different terms. One of them, directly linked to the apparatus type, is its own resistance, which in case of liquid extraction columns is manifested as pressure drop along the column height. The energy consumed in surmounting the column resistance depends on the particular apparatus and is an important parameter for the column design. To extend the existing state of knowledge and to provide additional information, we examined the energy consumption in a particular type of liquid extraction columns, namely pulsed extraction **c**olumns with internals of **d**iscs and **r**ings (doughnuts), abbreviated further as DRC. Till now the pulsed flow in these columns has been regarded as equivalent to a permanent one at the same velocity level. Our task was to examine the impact of the periodic flow pattern in order to enable for a more precise column design by developing a relation for determination of the energy consumption due to pressure drop in DRC with pulsed flow.

DRCs were invented 35 years ago, primarily for extraction processes in the nuclear industry and for recycling of nuclear fuel [1,2]. This type of equipment has shown good overall performance as a device for intensive and efficient mass transfer contact in liquid-liquid media, especially at heavy conditions requiring hermetic operation (aggressive liquids, radioactivity) [3,4]. In the course of time DRCs have found a number of civil applications, e.g., in hydrometallurgy, production of chemicals etc. [5-8]. They have also demonstrated ability for sustainable operation in the presence of some amount of solid inclusions, which are successfully washed out with the outlet flow because the large tray's apertures are not clogged by the solids [9]. Because of their good overall performance, recently they have become the subject of intensive research [10-14].

1. Previous Studies

In a previous paper [15] we showed that the existing practice for determination of pressure drop in a pulsed flow is based on the presumption that a pulsed flow with a given mean velocity is equivalent to a permanent flow with the same velocity [16,17]. Consequently, measurements taken in a permanent flow are representative of the pulsed flow, too. However, this assumption leads to underestimated results for pressure drop in the pulsed flow [15]. Consequently, the energy consumption determined on the same base would be unrealistic.

The classical equation for pressure drop in a permanent flow,

$$\Delta p = \rho g \Delta l = C\frac{Z}{D_c}\rho U^2, \tag{1}$$

states that pressure drop is proportional to the square of velocity U, the distance between measuring points Z and inversely proportional to the pipe diameter D_c, ρ is fluid density, g is gravity term, Δl is the differential manometer height. In the case of permanent flow C will correspond to the pressure drop coefficient for a permanent flow.

The pulsed flow generated by a piston pulsing device changes its velocity in every moment according to the expression [18,19]

$$U(t) = \pi A f \cos(2\pi f t) \tag{2}$$

with A and f being correspondingly pulsation amplitude and frequency, t is time.

The mean pulsation velocity U_m is obtained by integrating Eq. (2) over a period of pulsation T (T=1/f)

$$U_m = \frac{1}{T}\int_0^T |U(t)| = \int_0^T |\pi A f \cos(2\pi f t)| dt = 2Af \tag{3}$$

Eq. (3) is developed in detail in Appendix 1.

†To whom correspondence should be addressed.
E-mail: gang@bas.bg

Assuming that the pressure drop in a pulsed flow is proportional to the square of its velocity, one can replace the velocity term in (1) by the expression for mean pulsation velocity (Eq. 3). This assumption is explicitly supported by the experimental observation of other authors [16,20], stating that in both permanent and pulsed flows the energy (which is proportional to the product of pressure drop and velocity) is proportional to the cube of velocity.

Integration over a pulsation period T leads to

$$\frac{\Delta p D_c}{Z\rho}=\frac{1}{T}\int_0^T C(\pi A f)^2\cos^2(2\pi f t)dt$$

$$=\frac{\pi^2}{8}C(2Af)^2=C_p(2Af)^2=C_p U_m^2 \quad (4)$$

$$C_p=\frac{\pi^2}{8}C=1.234C \quad (5)$$

It is seen that the pressure drop coefficient for the pulsed flow C_p is about 25% greater than the that of an "equivalent" permanent flow C. Based on simulations with a turbulent flow model, a correlation for determination of pulsed flow pressure drop coefficient C_p has been developed and its validity has been confirmed experimentally [15]:

$$C_p=0.21F^{-2.80}\cdot h^{-0.85\ln F-2.74} \quad (6)$$

where F is plate free area, h is the ratio of interplate distance H and column diameter D_c ($h=H/D_c$).

The pressure drop characterizes the column resistance. Energy is consumed to overcome this resistance so as to make the flow passing through the column. A relation for determination of energy consumption due to pressure drop in DRC with pulsed flow is developed below.

ENERGY CONSUMPTION IN A PULSED FLOW

For a permanent flow, the energy E consumed for unity of mass and time is expressed by

$$E_t=\frac{Ug\Delta l}{Z} \quad (7)$$

Eq. (7) is derived in Appendix 2.

Introducing Δl expressed through Eq. (1), it is obtained

$$E_t D_c=CU^3 \quad (8)$$

This cubic dependence of energy consumption on flow velocity has been experimentally confirmed for a pulsed flow in DRC [16,20].

In case of a pulsed flow, the velocity and energy consumption depend on time and change in every moment during the pulsation. The mean energy consumption can be obtained by integration over a period of pulsation T:

$$E_m=\frac{1}{T}\int_0^T E(t)dt=\frac{1}{T}\int_0^T\frac{C}{D_c}|U(t)|^3dt=\frac{\pi^2}{6}\frac{C}{D_c}\cdot(2Af)^3 \quad (9)$$

$$E_m D_c=\frac{\pi^2}{6}C(2Af)^3=\frac{\pi^2}{6}CU_m^3=C_p^E U_m^3 \quad (10)$$

$$\text{with } C_p^E=\frac{\pi^2}{6}C=1.64C \quad (11)$$

or by use of Eq. (5)

$$C_p^E=\frac{4}{3}C_p \quad (12)$$

Comparing (8) and (10), the mean energy consumption of a pulsed flow E_m is $\pi^2/6=1.64$ times greater than that of an "equivalent" permanent flow at the same velocity.

E_m can be evaluated by experimental measurement of differential height loss Δl in a permanent flow. From Eqs. (1) and (10), it is obtained

$$E_m=\frac{\pi^2}{6}\frac{g\Delta l}{Z}U_m \quad (13)$$

Also, an easy access to E_m at different stage configurations is possible through correlation (6) for determination of C_p or by an expression for C_p^E derived by combining (6) and (12)

$$C_p^E=0.28F^{-2.80}\cdot h^{-0.85\ln F-2.74} \quad (14)$$

EXPERIMENTAL

1. General Apparatus Design

A DRC consists of cylindrical body filled with alternating immobile internals in the form of discs and rings (Fig. 1). They are placed in horizontal position and symmetrically with respect to the column axis.

The rings (called also doughnuts) are extended to the column wall, while the discs are placed in the center and do not reach the column wall. Two rings with a disc between them form a constructive stage. The dimensions of discs and rings are selected to offer the same free area to flow. Two types of passages are formed for the flow: central passages through the ring aperture and peripheral passages of annular form between the disc edge and column wall. The disc diameter is larger than the diameter of ring aperture, so as to hamper a direct flow in axial direction. A pulsing device induces pulsations to the fluids in the column, which creates intensive mixing conditions and turbulent operational regimes that are favorable for the process intensification.

Our particular DRC has the geometry parameters given below:

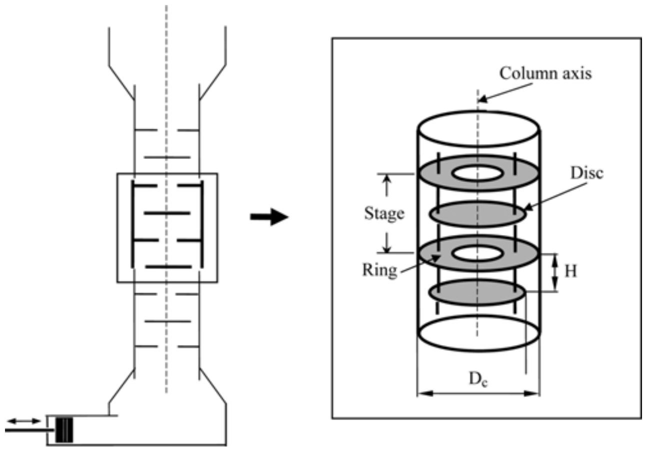

Fig. 1. A sketch of a DRC apparatus.

Column height 3.40 m.
Column diameter D_c=0.29 m.
Number of plates 51
Plate thickness 0.003 m
Interplate distance H=0.045 m, h=H/D_c=0.155
Plate free area F=0.23 (23%)
Height filled with plates 2.40 m
Distance between measuring points Z=0.66 m.

We have measured experimentally Δl in a permanent water flow by a differential manometer coupled at a distance of 0.66 m in the medium part of the column body, embracing 14 plates equivalent to 7 stages.

RESULTS

Correspondingly to the column volumetric output, the pulsed flow has some permanent velocity, which is usually 50-100 times lower than its pulsed velocity (=2Af - Eq. (3)) [21]. For this reason the permanent velocity component can be omitted and only the mean pulsed velocity can be considered for defining the dynamic conditions using the Reynolds number

$$Re=\frac{2AfD_c}{\nu} \tag{15}$$

with ν being cinematic viscosity.

Fig. 2 illustrates the mean energy consumption E_m of a pulsed flow at different Re numbers. Our experimental results for Δl have been measured at different flow velocity and converted to E_m through Eq. (13). The calculated results are obtained through Eq. (14) and (10) for the same conditions. Also, literature experimental data are plotted here [19]. They have been taken on an identical column with slightly smaller interplate distance, which results in slightly higher pressure drop and energy consumption.

Direct comparison of experimental and calculated results is plotted on Fig. 3. Good coincidence is observed (maximum about 3.5% for our results and about 10% for literature experimental data). It is an evidence for the reliability of the pro-

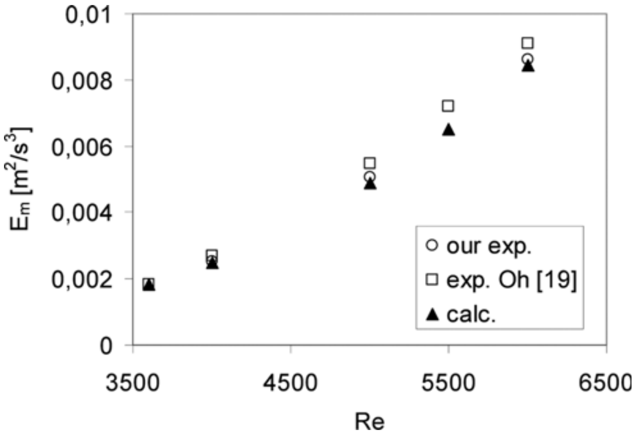

Fig. 2. Mean energy consumption at various Re numbers.

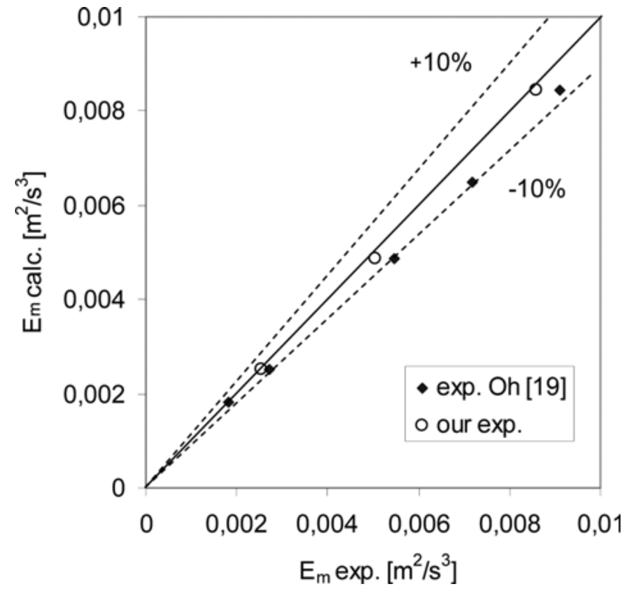

Fig. 3. Comparison of experimental (E_m exp) and calculated (E_m calc) results for the mean energy consumption.

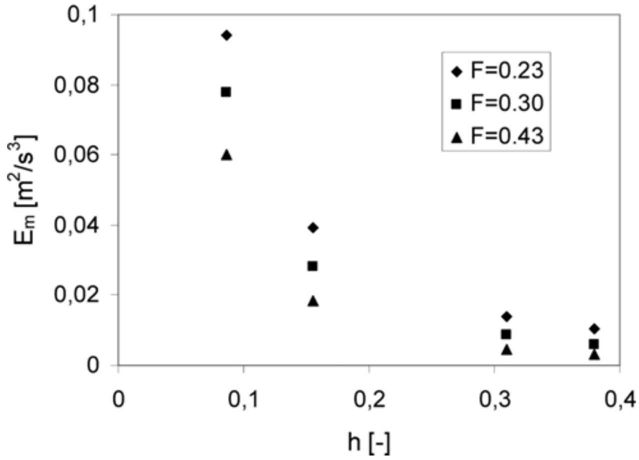

Fig. 4. Influence of interplate distance h on energy consumption per unit of mass at different plate free area F, Re=10000.

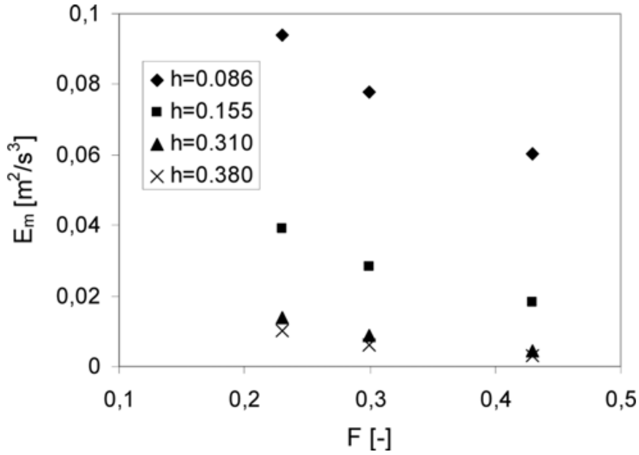

Fig. 5. Influence of plate free area F on energy consumption per unit of mass at different values of interplate distance h, Re=10000.

posed relation for determination of energy consumption due to pressure drop.

Fig. 4 illustrates the influence of interplate distance on energy consumption. It becomes smaller at larger interplate distance. The energy reduction is important up to values of h of about 0.3. For greater values of h its influence is not pronounced. This tendency is valid at different values of plate free area F.

Another presentation of the above results is shown at Fig. 5 to illustrate explicitly the impact of plate free area F on energy consumption.

Again, the influence of F is more important at smaller values of h and becomes negligible at h greater than 0.3. Thus, from the energy point of view a value of h around 0.3 seems to be optimal. It is useless to operate at interplate distance more than 0.3 because no energy will be saved. Moreover, there will be a negative effect of larger h on overall column efficiency due to reduced number of constructive stages in a unit of column height.

The data on Figs. 4 and 5 implies for a reasonable choice of F-value in the interval 0,2-0,4. This result conforms to the empirical experience, which recommends values of F 0,2-0,3 as favorable for column overall efficiency [22].

In a previous paper [23] we developed correlations for determination of turbulent flow parameters in DRC - turbulent kinetic energy k and turbulent macroscale L as depending on stage geometry parameters F and h.

$$k=\left[1.85+\left(\frac{1}{h}\right)^{0.67}\left(\frac{1}{F}-1\right)^{0.65}\right](Af)^2 \tag{16}$$

$$\frac{D_c}{L}=22.38+\left(\frac{1}{h}\right)^{1.49}\left(\frac{1}{F}-1\right)^{0.48} \tag{17}$$

The turbulent energy dissipation rate ε can be determined from the basic equation of k-ε turbulent model

$$\varepsilon=C_L\frac{k^{3/2}}{L} \tag{18}$$

where the coefficient C_L takes values from 0.4 to 1.1 depending of apparatus geometry [24]. As it was found, C_L=0.4 represents well the results for turbulent flow parameters in columns of this type [25].

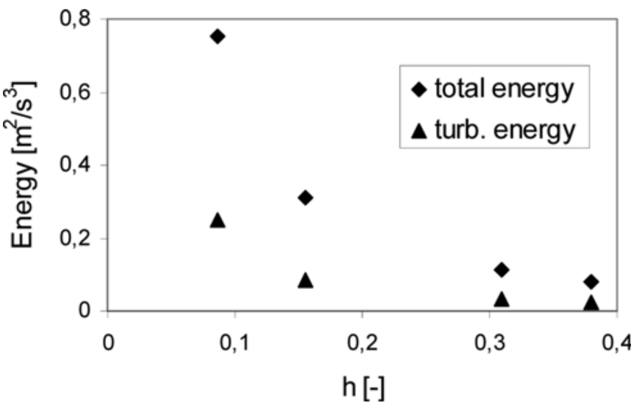

Fig. 6. Total and turbulent energy dissipation rate per unit mass at different interplate distance Re=10000, F=0.23.

The dissipated turbulent kinetic energy represents only the transformation of turbulent kinetic energy into heat. The energy consumption considered here includes all energy losses associated with the flow passing through the column. Consequently, this global energy consumption should be greater than the turbulent energy dissipation.

Fig. 6 compares these two energy losses determined by relations (10,14,16-18). A logical result is seen, showing that the total energy consumption is significantly higher than the turbulent energy dissipation rate. It might be considered as an additional qualitative evidence for the reliability of the proposed correlation for evaluation of the energy necessary for passing of a pulsed flow through a column with internals of discs and rings.

CONCLUSION

The results of this study have shown that a pulsed flow cannot be regarded as a permanent one with velocity equal to the mean velocity of the pulsed flow. The mean energy consumption due to pressure drop in case of a pulsed flow is found to be about 65% greater. A correlation for determination of mean energy consumption in column apparatuses with internals of discs and rings in case of pulsed flow is proposed. It is useful for design purposes, namely for determination of energy losses due to pressure drop at different geometry parameters of the column - plate free area and interplate distance and at different pulsation parameters. Thus, it is helpful for optimization of stage geometry targeted to lower energy consumption. A check for precision of the proposed relations has shown good agreement with experimental data.

SYMBOLS USED

A : pulsation amplitude [m]
C : pressure drop coefficient for a permanents flow (in Eq. (1)) [-]
C_p : pressure drop coefficient for a pulsed flow (in Eq. (4)) [-]
C_p^E : coefficient in Eq. (10) [-]
C_L : coefficient in Eq. (17) [-]
D_c : column diameter [m]
E(t) : instantaneous energy, pulsed flow [m^2/s^3]
E_t : energy per unity of mass and time, permanent flow [m^2/s^3]
E_m : mean energy per unity of mass and time, pulsed flow [m^2/s^3]
F : plate free area [-]
f : pulsation frequency [1/s]
G : force [N]
g : gravity [m/s^2]
H : interplate distance [m]
h : geometry ratio=H/Dc [-]
k : turbulent kinetic energy [m^2/s^2]
L : turbulent macroscale [m]
Δl : differential manometer height [m]
Δp : pressure drop [N/m^2]
Re : Reynolds number [-]
S : column cross section [m^2]
t : time [s]
T : pulsation period [s]

U : flow velocity [m/s]
U(t) : instantaneous flow velocity, pulsed flow [m/s]
U_m : mean velocity, pulsed flow [m/s]
W : work [Nm, J]
Z : distance between measuring points [m]

Greek Symbols
ε : turbulent energy dissipation rate [m^2/s^3]
ρ : flow density [kg/m^3]
ν : cinematic viscosity [m^2/s]

REFERENCES

1. P. Faugeras, E. Henry, R. Malaterre and P. Fremeaux, Patent BF N En 78.36388 (1978).
2. F. Chenevier and C. Bernard, *Nucl. Eng. Int.*, **32**, 397, 41 (1987).
3. C. Musikas and W. Schulz, in *Principles and practice of solvent extraction*, Marcel Dekker Inc., New York (1992).
4. A. Cocaud, D. Guilloteau and P. Houdin, *Trans. Amer. Nucl. Soc.*, **91**, 505 (2004).
5. A. Feather, W. Bouwer, A. Swarts and V. Nagel, *Proc. Int. Solvent Extraction Conf.*, Chris van Rensburg Pub., Johannesburg, South Africa (2002).
6. C. Mason, B. Grinbaum, J. Harlamovs and D. Dreisinger, *Proc. Hydrometallurgy'03*, 765, Vancouver, Canada (2003).
7. N. J. M. Kuipers, B. Kuzmanovic, A. B. De Haan and G. Kwant, *Chemie-Ingenieur-Technik*, **76**, 9, 1409 (2004).
8. M. L. Van Delden, N. J. M. Kuipers and A. B. De Haan, *Sol. Extr. Ion Exchange*, **24**, 4, 499 (2006).
9. R. L. Mosvovitz, R. Kleinberger, E. M. Buchalter, B. Grinbaum and S. Hall, in *Solvent extraction for the 21st century*, M. Cox, (Ed.), Soc. Chem. Ind., London (2001).
10. S. Bi, S. Jing, Q. Wu and J. Chen, *Atomic Energy Sci. Technol.*, **41**, 4, 410 (2007).
11. G. U. Din, I. R. Chughtai, M. H. Inayat, I. H. Khan and N. K. Qazi, *Sep. Purif. Technol.*, **73**, 2, 302 (2010).
12. M. Torab-Mostaedi, A. Ghaemi and M. Asadollahzadeh, *Chem. Eng. Res. Design*, **89**, 12, 2742 (2011).
13. S. Charton, J. Duhamet, G. Borda and D. Ode, *Chem. Eng. Sci.*, **75**, 468 (2012).
14. M. Torab-Mostaedi, A. Ghaemi and M. Asadollahzadeh, *Can. J. Chem. Eng.*, **90**, 6, 1570 (2012).
15. G. Angelov and C. Gourdon, *Chem. Eng. Res. Design*, **90**, 7, 877 (2012).
16. J.-F. Milot, J. Duhamet, C. Gourdon and G. Casamatta, *Chem. Eng. J.*, **45**, 2, 111 (1990).
17. P. Leroy, Ph. D. Thesis, INP-Lorraine (1991).
18. S. K. Agraval, *Fluid mechanics and machinery*, 11th Reprint, 503, McGraw-Hill, Delhi (2006).
19. W. Oh, Ph. D. Thesis, INP-Toulouse (1984).
20. A. Laulan, Ph. D. Thesis, INP-Toulouse (1980).
21. M. Buratti, Ph. D. Thesis, INP-Lorraine (1988).
22. Perry's Chemical Engineers' Handbook, 8th Ed., D. Green (Ed.), McGraw-Hill, 15-74 (2008).
23. G. Angelov and C. Gourdon, in *Value Adding Through Solvent Extraction*, D. Shallcross (Ed.), 1109 (1996).
24. B. E. Launder and D. B. Spalding, *Mathematical models of turbulence*, Academic Press, London, New York (1972).
25. G. Angelov, *Flow hydrodynamics in pulsed extraction columns with discs and rings*, D. Sci. Thesis, Bulg. Acad. Sci, Sofia (2008).

APPENDIX 1

Derivation of Eq. (3)
The period of pulsation T=1/f
So, the expression for U(t) (Eq. (2)) can be rewritten as

$$U(t)=\pi Af\cos(2\pi t/T) \tag{1.1}$$

The graph of velocity evolution in the course of time is presented at Fig. 1.1 below.

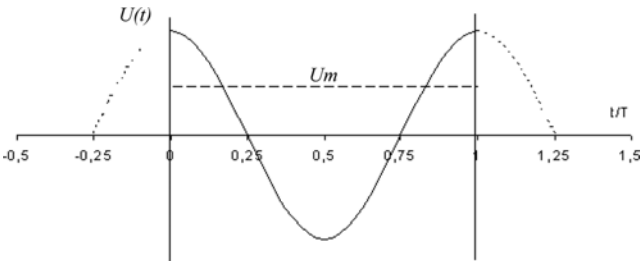

Fig. 1.1.

The energy is consumed by the flow with both positive and negative velocity. If integrated directly over the interval 0 to T, the mean velocity will be zero, because for the half of the interval the velocity is equal to the other half, but with opposite sign. For this reason we integrate the absolute value of the velocity.

To obtain the value of mean velocity we divide the period of pulsation in three zones.

First zone - time interval 0 to T/4. The velocity is positive.

$$U_{m1}=\frac{1}{T/4}\int_0^{T/4}\pi Af\cos(2\pi t/T)dt$$

$$=2Af\int_0^{T/4}d(\sin 2\pi t/T)=2Af(\sin\pi/2-\sin 0)=2Af \tag{1.2}$$

Second zone - time interval T/4 to 3/4T - velocity is negative and we take its absolute value.

$$|U_{m2}|=\frac{1}{T/2}\int_{T/4}^{3T/4}|\pi Af\cos(2\pi t/T)|dt=Af\int_{T/4}^{3T/4}d(\sin 2\pi t/T)$$

$$=Af|(\sin 3\pi/2-\sin\pi/2)|=Af|-1-1|=2Af \tag{1.3}$$

Third zone - time interval 3/4T to T - positive velocity.
It is analogous to the first zone and the result is the same

$$U_{m3}=2Af \tag{1.4}$$

So, the mean velocity during all parts of the whole period of pulsation T is

$$U_m=2Af \qquad (1.5)=(\text{Eq. }3)$$

APPENDIX 2

Derivation of Eq. (7)

$$E=W=F\cdot Z \tag{2.1}$$

$$\Delta p=F/S \tag{2.2}$$

From (2.2)

$$F=\Delta p\cdot S \tag{2.3}$$

Replacing F in (2.1) by (2.3)

$$E=\Delta p\cdot S\cdot Z \tag{2.4}$$

$$\Delta p=\rho\cdot g\cdot \Delta l \tag{2.5}$$

Replacing Δp in (2.4) by (2.5)

$$E=\rho\cdot g\cdot \Delta l\cdot S\cdot Z \tag{2.6}$$

$$S\cdot Z=V \tag{2.7}$$

$$V\cdot \rho=m \tag{2.8}$$

Introducing (2.7) and (2.8) in (2.6)

$$E=g\cdot \Delta l\cdot m \tag{2.9}$$

Energy per unity of mass and time

$$E/(t\cdot m)=g\cdot \Delta l/t \tag{2.10}$$

$$t=Z/Um \tag{2.11}$$

$$E=g\cdot \Delta l\cdot Um/Z \qquad \text{(2.12)=Eq. (7)}$$