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An Experimental Analysis of Airflow in Various Collapsible Tubes at the Onset of Self-Excited Oscillations

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Original scientific paper

The experimental results of airflow through some collapsible tubes are analysed in this paper for the case of onset of self-excited oscillations without so much focusing on the mechanisms triggering the oscillations. The basic experimental measurements are the pressure values at both of upstream and downstream ends of the collapsible tube as well as velocity at downstream of the tube by means of a hot wire anemometer. The obtained results correspond to the instant at which oscillations appear. It has been established that the flow is substantially chaotic during the vigorous oscillations. The experimental data at the onset of self-excited oscillations was evaluated subsequently to obtain some non-dimensional parameters based on oscillating flow velocity, frequency, pressure drop through the collapsible tube and downstream transmural pressure. The variations of these parameters with some terms including all geometrical and mechanical characteristics of the collapsible tubes are presented. The diversity of experimental variables such as collapsible tube type, tube-wall thickness, tube length and flow rate which are varied in the investigation should be useful on account of having a general information about collapsible tube flow researches. It has been recognized that all of these variables considerably affected the behaviour (frequency, velocity, upstream and downstream pressure) of oscillations and conditions of their emergence. It can thereby be suggested that the specifications of the tube should be carefully considered in the collapsible tube flow investigations.

Eksperimentalna analiza zračnog toka u sklopivim cijevima pri pojavi samopobudnih oscilacija

Izvornoznanstveni članak

U ovom radu se analizira eksperimentalne rezultate mjerenja zračnog toka kroz sklopive cijevi za slučaj samopobudnih oscilacija, bez mnogo razmatranja mehanizama koji pokreću oscilacije. Osnovna eksperimentalna mjerenja su vrijednosti tlaka na uzstrujnom i nizstrujnom kraju sklopive cijevi te brzina na nizstrujnom kraju mjerena pomoću anemometra s vrućom žicom. Dobiveni rezultati se podaudaraju do trenutka pojave oscilacija. Ustanovljeno je da je protok prilično kaotičan tijekom snažnih oscilacija. Eksperimentalni podaci pri nastanku samopobudnih oscilacija su naknadno evaluirani kako bi se dobilo neke bezdimenzijske parametre vezane uz brzinu oscilatornog protoka, frekvenciju, pad tlaka kroz sklopivu cijev i nizstrujni tlak kroz stijenku. Prikazane su varijacije tih parametara po nekim članovima izraza uključujući sve geometrijske i mehaničke karakteristike sklopivih cijevi. Raznolikost eksperimentalnih varijabli poput vrste cijevi, debljine stijenke cijevi, duljine cijevi i brzine protoka variranih u istraživanju trebala bi biti korisna zbog sadržanih općih informacija za istraživanja sklopivih cijevi. Prepoznato je da sve navedene varijable značajno utiču na svojstva (frekvenciju, brzinu, uzstrujni i nizstrujni tlak) oscilacija i uvjete njihovog pojavljivanja. Stoga se može preporučiti pažljivo razmatranje tehničkog opisa cijevi u istraživanjima sklopivih cijevi.

Keywords
Collapsible tube flow
Fluid-structure interaction
Self-excited oscillations onset
Wall inertia

Ključne riječi
Inercije stijenke
Interakcija fluida i struktura
Nastanak samopobudnih oscilacija
Strujanje u sklopivim cijevima

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1. Introduction

The collapsible tube flows have been studied experimentally and theoretically by a number of researchers due to their relative connection to physiological flows and they can also be regarded as a general interdisciplinary engineering subject, i.e. a challenging fluid-structure interaction problem. It has

Symbols/Oznake

A_o	- cross-sectional area of the circular tube - površina poprečnog presijeka kružne cijevi	$\bar{p}_2$	- time average of $p2$ - vremenski osrednjen nizstrujni tlak
D_o	- inside diameter of the circular tube - unutarnji promjer kružne cijevi	Q	- steady flow rate - stacionarni volumni protok
E	- modulus of elasticity of the tube material - modul elastičnosti materijala cijevi	R_o	- inside radius of the circular tube - unutarnji polumjer kružne cijevi
f	- frequency of the oscillations - frekvencija oscilacija	Re	- Reynolds number of steady flow - Reynoldsov broj stacionarnog toka
h	- wall thickness of the tube - debljina stijenke cijevi	t	- time - vrijeme
K_p	- circumferential bending stiffness of the tube - krutost na savijanje po opsegu cijevi	u	- oscillating flow velocity - brzina oscilirajućeg toka
L	- length of the collapsible tube - duljina sklopive cijevi	$\bar{u}_{os}$	- time average of u - vremenski osrednjena u
p_e	- external pressure - vanjski tlak	$\bar{u}$	- steady mean fluid velocity - srednja vrijednost stacionarne brzine fluida
$p_{e,c}$	- external pressure at collapse - vanjski tlak na sklapanju	v	- Poisson's ratio of the tube material - Poissonov broj materijala cijevi
p_1	- upstream pressure - uzstrujni tlak	v_f	- kinematic viscosity of the fluid - kinematska viskoznost fluida
$\bar{p}_1$	- time average of $p1$ - vremenski osrednjen uzstrujni tlak	ρ_f	- density of the fluid - gustoća fluida
p_2	- downstream pressure - nizstrujni tlak	ρ_w	- density of the tube material - gustoća materijala cijevi

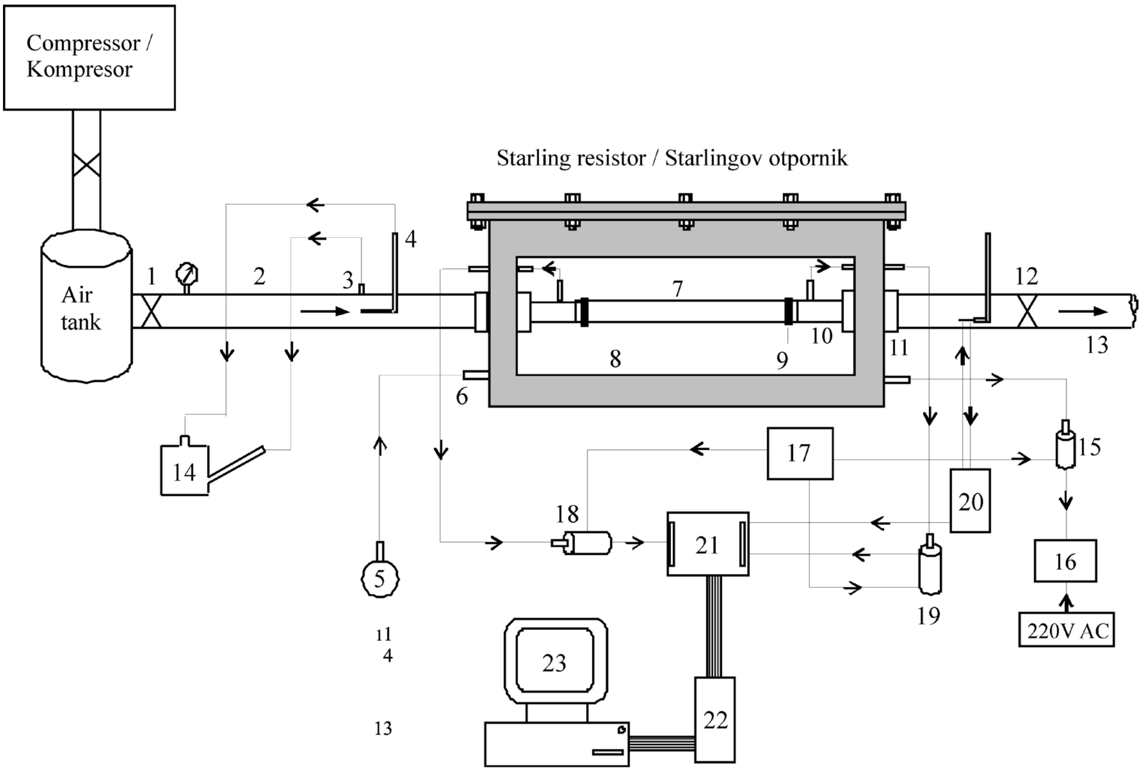
been usually observed and recorded that chaotic self-excited oscillations develop strongly in both of tube wall and flow when the internal minus external pressure across the tube wall so called "transmural pressure" is negative. In the collapsible tube flow experiments, a vigorous interaction occurs inevitably between tube-wall and flow. The self-excited oscillations with a multiple frequency mode emerge owing to this interaction [1] and the flow field becomes too complicated thereby. In general the oscillations are affected by both of tube characteristics and flowing fluid. So far, the investigators studied the topic with theoretical study [2] or experimental work [3] to bring out the potential mechanisms inducing the oscillations to develop. Water was mostly used as flowing fluid in the experimental practises [4], however in a few researches [5,6] air was preferred as fluid. In fact, Bertram and Chen [7] have pointed out that there is a need for the investigations with airflow through collapsible tubes.

The investigations on the flow through collapsible tubes should probably have a considerable significance in the biomedical and biomechanical applications. It is therefore useful at this point to mention about the relevance of the collapsible tube flows with physiology. In the cardiovascular system, self-excited oscillations arise in the veins above heart [8]. Tsuji *et al.* [9] have observed self-excited oscillations in the coronary heart veins during open-heart surgery. The Korotkoff sounds [10] heard during blood pressure measurement are directly due to the self-excited oscillations developed in the arm's veins. Griffiths [11] has expressed that flow behaviour in the urethra is very similar to that through a collapsible tube. In addition, the collapsibility of the lung airways has a severe influence upon the flow in the lung. Gavriely *et al.* [12] have considered that the self-excited oscillations develop with different respiration sounds in the collapsible lung airways. Berke *et al.* [13] has claimed that the generation of voice is related to the control of flow-induced oscillations of the flexible vocal chords. Gavriely and Jensen [14] pointed out that the source of snoring sounds which arise in the course of sleeping is directly based on the flow-induced deformation of pharynx wall and soft palate.

In this paper, experimental results of airflow through collapsible silicone rubber tubes and Penrose tubes which are under the effect of external pressure are analysed by disregarding physiological relevance of the topic. The primary results are presented as the unsteady pressure and velocity measurements which have been recorded instantaneously at oscillations onset. As well as flow rate, experimental variables concerning the collapsible tube specifications such as length and thickness of the tubes are used within a comprehensive manner. Moreover, some important dimensionless terms which have been determined systematically covering flow properties and both of the tube's geometrical and mechanical specifications are presented. Then relationship between the introduced terms is obtained and results are analysed for deciding how considered experimental variables affect flow in collapsible tubes.

2. Description of the experimental set-up and characteristics of the tested collapsible tubes

The experimental set-up is presented in Reference [15] and it is shown in Figure 1. A brief description of the system is offered hereby in this paper. The collapsible tube was placed in an airtight chamber horizontally and it was attached to rigid pipe segments with clamps at upstream and downstream ends. Since the apparatus was firstly used by Starling and his colleagues [16], the airtight box including a collapsible (latex or silicone) tube under the effect of external pressure (p_e) is known as "Starling resistor". Steady airflow was delivered to the experimental set-up from a screw-type compressor and steady flow rate amount (Q) was fixed with a pressure regulator. The magnitude of Q was measured by means of a Pitot tube assembled to an inclined leg alcohol-manometer (steady mean flow velocity $\overline{u}$ determined via Pitot tube is in fact directly converted into flow rate as Q=$A_o\overline{u}$ where A_o is cross-sectional area of the circular tube). The sensitivity in Q measurement was ±0.0015 m^3/s. Starling resistor was pressurized through a manual air pump and p_e was



1. pressure regulator / regulator pritiska
2. upstream rigid pipe / uzstrujna kruta cijev
3. static pressure tapping / otvor za statički tlak
4. Pitot tube / Pitotova cijev
5. manual air pump / ručna pumpa zraka
6. p_e application valve / ventil za p_e
7. collapsible tube / sklopiva cijev
8. observation window / prozor za promatranje
9. clamps / stege
10. rigid attachments / kruti priključak
11. connection parts with O- ring / spojni dijelovi s O-prstenom
12. downstream valve / nizstrujni ventil
13. downstream rigid pipe / nizstrujna kruta cijev
14. inclined manometer for measuring Q / nagnuti manometar za mjerenje Q
15. pressure transmitter / pretvarač signala tlaka
16. digital process controller / digitalni procesni kontroler
17. DC power supply / izvor istosmjerne struje
18. pressure transducer for measuring p_1 / transduktor tlaka za p_1
19. pressure transducer for measuring p_2 / transduktor tlaka za p_2
20. hot-wire anemometer / anemometar s toplom žicom
21. accessory board / ploča za dodatke
22. data acquisition hardware / oprema za akviziciju podataka
23. computer / računalo

Figure 1. A schematic representation of the experimental set-up

Slika 1. Shematski prikaz eksperimentalnog aparata measured by a pressure transmitter. The time dependent upstream pressure (p_1) and downstream pressure (p_2) of the tube were recorded through pressure transducers with a sensitivity of ±10 Pa. The oscillating flow velocity (u) at the exit of Starling resistor was measured through a hot-wire anemometer with a sensitivity of ±0.05 m/s. The probe of the hot-wire anemometer was fixed at a distance of 0.76 R_o (where R_o is the inside radius of the circular tube) from the pipe centre and the mean velocity of oscillating flow has therefore been determined at this position of the probe. The voltage outputs from hot-wire anemometer and pressure transducers were accumulated on a computer by the agency of data acquisition system.

In the experimental work, silicon rubber tube (wall density of tube material, ρ_w=1200 kg/m^3) and latex-made Penrose tube (ρ_w=1020 kg/m^3) were used as collapsible tubes with an inside diameter (D_o) of 25.4 mm when the tubes are circular in cross-section. The tube was placed in the centre of Starling resistor without applying any longitudinal tension. The coding system for collapsible tubes together with their length (L), length to diameter ratio L / D_o, tube-wall thickness (h) and ratio of the inside radius to the tube-wall thickness (R_o / h) are represented in Table 1. As an example for the coding system; $S_{2,S}$ defines silicone rubber tube for which L = 127 mm and h = 2 mm, namely subscript numbers indicate tube thickness while the subscript letters L, M and S imply long, medium and short tubes, respectively. The tubes having R_o/h >10 and R_o/h <10 are classified as thin-walled and thick-walled, respectively.

The value indicating the modulus of elasticity of the tube material E, which was determined in the axial force-deflection test, is also introduced in Table 1. The symbol K_p seen in the last column of Table 1 is the circumferential bending stiffness of the test tubes which can be obtained by means of the following relationship:

$$K_p = \frac{1}{12} E \frac{(h / R_o)^3}{(1-v^2)}, \tag{1}$$

where v is Poisson's ratio for the material of the collapsible tube and it is supposed to be 0.48 which is widely accepted as an approximate value for rubber materials. It should be remarked that K_p has the unit of pressure, i.e., Pascal as Eq. (1) yields. It can thereby be deduced by referring to Table 1 that a wide range based on tube specifications has been covered through the experimental investigation.

2.1. Checking of reliability of the measurements

It has been known that some noise could be present in the system and surroundings, which may affect the electronic output of the devices. Therefore, the measurements were checked to verify whether the noises were effective on the experimental data. Initially the data from hot wire anemometer was acquired for a case when there is no airflow in the system and the measurements were recorded to the computer. Then a steady flow case was supplied to the system with ρ_o = 0 Pa, the data acquired and stored for this case. Subsequently an oscillating flow case was created by applying p_e into the Starling resistor while the same flow rate was present inside the collapsible tube. This oscillating flow was also measured by means of the data acquisition system. The result of above-mentioned process has been plotted as shown in Figure 2. It can be seen from Figure 2 that there are some differences between all of the cases. Namely, oscillating and non-oscillating flow can be easily distinguished from each other and furthermore the no-flow case is very far from those two cases. The no-flow case has a nearly constant value of 1.6 Volts which is actually the output voltage from hot-wire anemometer. Since it is constant and there is no considerable fluctuation of the no-flow case it can be said that the measurements will not be

Table 1. Specifications of the collapsible tubes utilized in the experiments

Tablica 1. Tehnički opis sklopivih cijevi korištenih u eksperimentu

Material / Materijal	Tube Code / Oznaka cijevi	L, mm	L/D_o	h, mm	R_o / h	Classification / Klasifikacija	E, Pa	K_p, Pa
Latex (Penrose Tube) / Lateks (Penrose drenažna cijev)	P_L	254	10	0.55	23.09	thin-walled / tankostijena	1.20E+06	10.55
	P_M	190.5	7.5					
	P_S	127	5					
Silicone Rubber / Silikon guma	$S_{1,L}$	254	10	1	12.7	thin-walled / tankostijena	2.03E+06	107.31
	$S_{1,M}$	190.5	7.5					
	$S_{1,S}$	127	5					
	$S_{2,L}$	254	10	2	6.35	thin-walled / tankostijena	2.03E+06	858.48
	$S_{2,M}$	190.5	7.5					
	$S_{2,S}$	127	5					

influenced by the system's natural noise. Moreover, the measurement of steady flow case does not change noteworthy with time as expected and it is approximately 2.55 Volts. However, oscillating flow is strongly changing with time; the output voltage is fluctuating between 1.9 Volts and 2.7 Volts.

The frequency is also another verification of insignificance of the possible noise present in the system. Therefore, FFT analysis of Figure 2 was carried out and the result is obtained as shown in Figure 3. It is clear that frequency has no peak value and it has a magnitude of nearly zero in no-flow and steady flow cases, as expected. Because steady flow does not oscillate at all and any frequency value could not be stated for this condition as well as no-flow case. However oscillating flow exactly shows a peak magnitude value of 0.12 at 20 Hz, approximately in comparison to the other two cases. As a result, by referring to Figure 2 and/or Figure 3, it can be definitely concluded that any noise which may be present in the system does not affect the flow measurements.

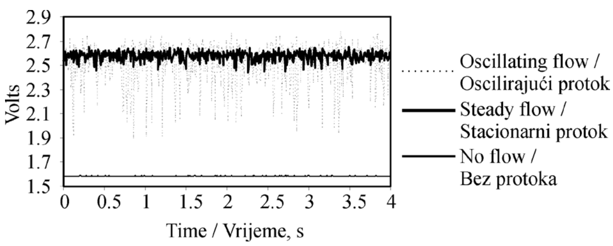


Figure 2. Sample measurement cases with hot wire anemometer to check the accuracy of the measurements

Slika 2. Uzorak mjerenja anemometrom s vrućom žicom radi provjere mjerne točnosti

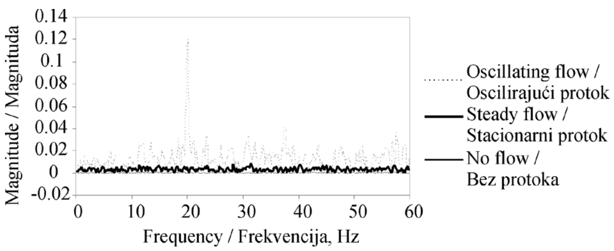


Figure 3. FFT analysis of Figure 2

Slika 3. FFT analiza Slike 2.

3. Basic experimental methods and results of the measurements

In this section experimental protocols followed in the study are outlined and the obtained results are then presented. The collapsible tubes specified in Table 1 were separately tested and experimental measurements were acquired for different Q values. In comparison to most of the previous investigations (e.g., [17]) p_1 or p_2 was kept constant as well as p_e while Q was varying, the experimental protocol in the present study was such that any Q was steadily provided to the system at $p_e = 0$ kPa (gauge) initially and p_e was gradually increased independently. The recording of measurements has been started as soon as flow suddenly becomes oscillating following a collapse near the tube's downstream end. The external pressure value giving rise to self-excited oscillations to develop has been regarded as the external pressure at collapse, $p_{e,c}$. The time-dependent p_1, p_2 and u magnitudes at this instant were saved to the computer in terms of voltages which were then converted into required unit of pressure and velocity according to the calibration results of the pressure transducers and hot-wire anemometer. The time average of p_1, p_2 and u were determined from oscillating flow measurements and the obtained time-averaged pressures and velocity were represented as $\overline{p}_1$, $\overline{p}_2$, $\overline{u}_{os}$, respectively. In addition the frequency of the oscillations (f) has been obtained by applying Fast Fourier Transform (FFT) to the oscillating pressure and/or velocity data.

The variations for the data of p_1, p_2 and u with time (t) are demonstrated as sample plots in Figure 4. These figures were plotted from the results of testing P_L tube with $Q = 0.0083$ m^3/s and $p_{e,c} = 0.16$ kPa which triggers the appearance of oscillations at the supplied flow rate. It is apparent in Figure 4 that pressure and velocity change distinctly with time. Furthermore it is obvious in Figure 4 that p_2 is more influenced in comparison with p_1, namely p_1 fluctuates as 0.2 kPa $< p_1 <$ 3.9 kPa, but p_2 alternates as –2.5 kPa $< p_2 <$ 2.4 kPa. This can be interpreted as a reasonable consequence since pressure decreases in the flow direction, accordingly transmural pressure will become negative near the exit of the tube and eventually tube wall collapses at that point. The oscillations arise strongly near the tube downstream end, then they can affect the tube's upstream end as well, ultimately p_1 also varies with time. It should be noticed besides that p_2 has negative magnitudes from time to time due to presence of the oscillations. It can be remarked by observing velocity distribution with time in Figure 4 that u is varying as 1.3 m/s $< u <$ 30 m/s. The experimental data in Figure 4 has been analyzed and time-averaged pressure and velocity quantities were calculated as $\overline{p}_1 = 1.18$ kPa, $\overline{p}_2 = 0.30$ kPa and $\overline{u}_{os} = 15.27$ m/s.

Figure 5 was obtained by carrying out FFT to the data present in Figure 4 and frequency was found to be $f = 19$ Hz corresponding to the peak magnitudes of p_1, p_2 and u. As expected, applying FFT to the time dependent variation of p_1, p_2 or u does not alter f value and this case can be clearly verified in Figure 5. The measured frequency values were also confirmed with a theoretical study [18].

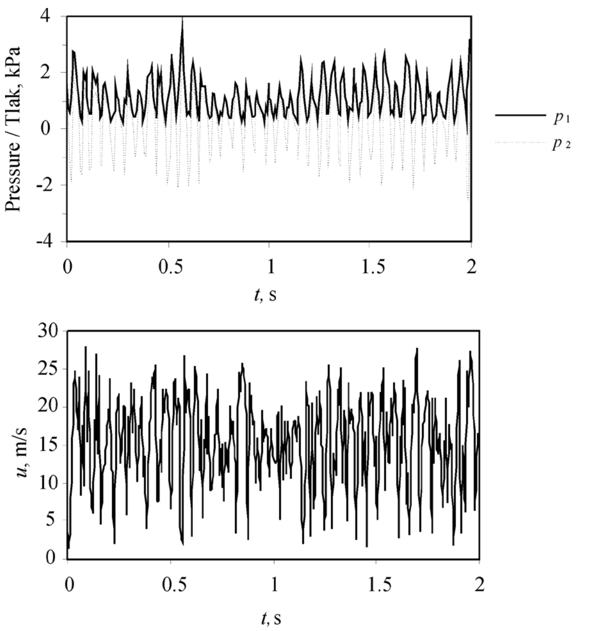


Figure 4. Variation of pressure and velocity with time at the onset of oscillations for the flow through P_L tube ($\bar{p}_1$ kPa, $\bar{p}_2$ kPa, $\bar{u}_{os}$ m/s)

Slika 4. Varijacije tlaka i brzine u vremenu pri nastanku oscilacija za protok kroz cijev P_L ($\bar{p}_1$ kPa, $\bar{p}_2$ kPa, $\bar{u}_{os}$ m/s)

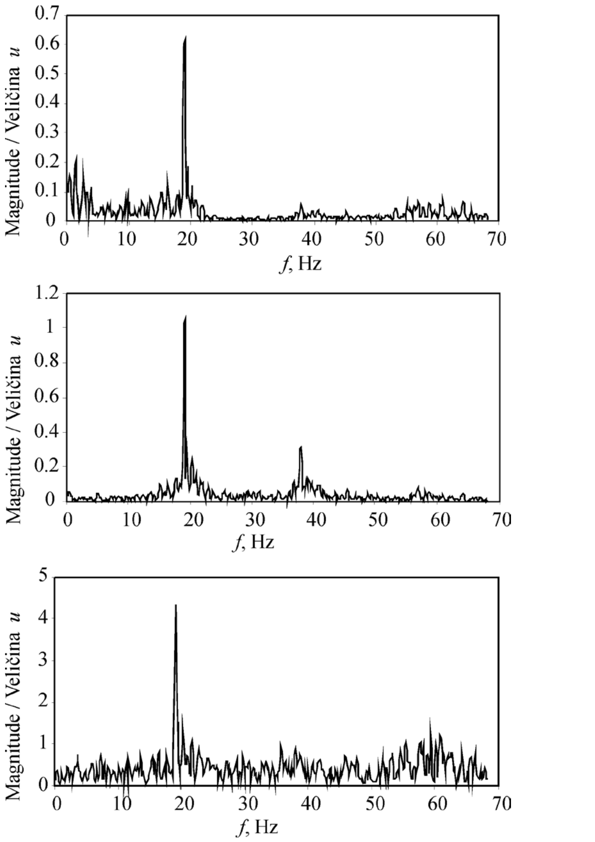


Figure 5. FFT analysis of Figure 4 (at the peak, f = 19 Hz for the three cases)

Slika 5. FFT analiza Slike 4 (na maksimumu amplitude f=19 Hz za sva tri slučaja)

3.1. Effect of tube-wall thickness on the flow behaviour

The collapsible tubes specified in Table 1 were tested with airflow [19] similarly to the results reported in Figure 4 for P_L tube (the experimental data with $S_{2,S}$ tube for $Q = 0.0147$ m^3/s and $p_{e,c} = 9.03$ kPa is given in [20]). The principal results of present investigation are shown in Figure 6 and Figure 7. The overall effect of h on $p_{e,c}$ can be understood in Figure 6. It is easily concluded by making comment on Figure 6(a) that the thicker tube wall causes $p_{e,c}$ to increase drastically at a specific Q value, namely $p_{e,c}$ is approximately 0.25 kPa, 2 kPa and 9 kPa for the flow through P_L, $S_{1,L}$ and $S_{2,L}$ tubes, respectively at $Q = 0.0101$ m^3/s. This corollary is also true for the remaining Q values. It is once observed from Figure 6 (b,c) that $p_{e,c}$ increases strictly as h becomes higher. Moreover, $p_{e,c}$ changes nearly between 0.25 kPa and 2 kPa for the covered Q and L values of Penrose tubes in Fig. 6. Similarly, it is changing between 2 kPa and 3 kPa for silicone rubber tubes with $h = 1$ mm. On the other hand $p_{e,c}$ range has risen dramatically as 8 kPa $< p_{e,c} <$ 10 kPa for 2 mm thick silicone rubber tubes regardless of Q.

The influence of h on f is presented with the plots in Figure 7. It seems by considering the data for silicon rubber tubes roughly that f increases with h at a particular Q. For instance if the case with $Q = 0.0101$ m^3/s is referred in Figure 7(a) it will be noticed that $f = 20$ Hz and 30 Hz for $S_{1,L}$ and $S_{2,L}$ tubes, respectively. Similarly this conclusion can also be recognized from Figure 7(b,c). However it would not be true based on the same comparison between silicone rubber and penrose tube since their specifications are rather different. It could be inferred by consulting to Figure 7 that f is in the order of 20 Hz regardless of L for Penrose tubes. On the other hand a range of 20 Hz $< f <$ 25 Hz is existent for thin-walled silicone rubber tube independent of L. Meanwhile it is evident for thick-walled silicone rubber tubes that frequency changes between 25 Hz and 35 Hz covering the given tube lengths. In summary, it can be roughly stated that if h increases, f and especially $p_{e,c}$ will also increase for a specific collapsible tube.

3.2. Effect of tube length on the flow behaviour

The effect of L on the flow behaviour can be examined by observing Figure 8 and Figure 9. Variation of $p_{e,c}$ with Q is given in Figure 8 for Penrose tubes with different L. It can be claimed that L has no significant influence on $p_{e,c}$. Nevertheless, $p_{e,c}$ negligibly increases as L becomes shorter and this issue can be supported by paying attention to $Q = 0.0213$ m^3/s case, for example. Therefore it can be deduced that L may have some effect on $p_{e,c}$. Higher

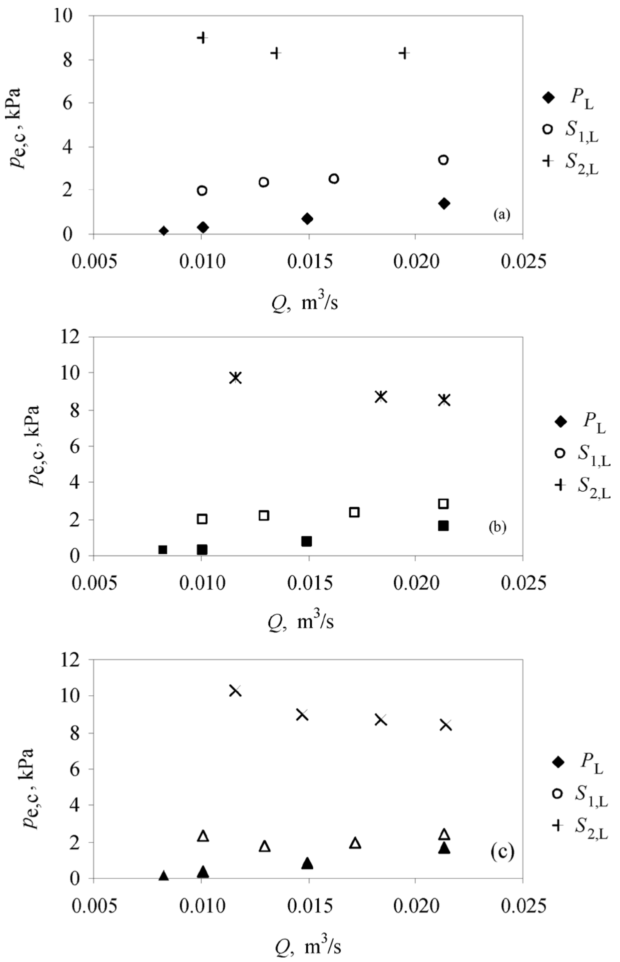


Figure 6. Variation of $p_{e,c}$ with Q to show the effect of thickness of the test tubes

Slika 6. Varijacije $p_{e,c}$ po Q za primjer utjecaja debljine stijenke ispitnih cijevi

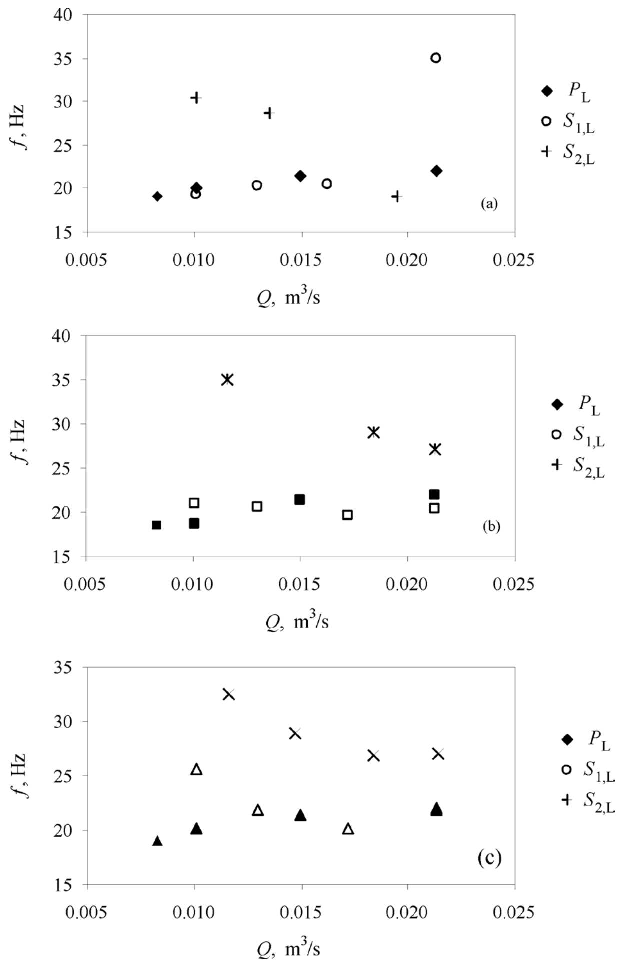


Figure 7. Variation of f with Q to show the effect of thickness of the test tubes

Slika 7. Varijacije f po Q za primjer utjecaja debljine stijenke ispitnih cijevi

$p_{e,c}$ required for a shorter tube means that as L decreases the tube will be more stiffer to be collapsed, that is the shorter tube may act as a rigid tube. The effect of L on f is shown in Figure 9. It can be said that f increases slightly for a shorter tube at a given Q.

4. Expression of experimental data in non-dimensional terms

In this section results of the experimental measurements are expressed in terms of dimensionless parameters which will surely enable more general information about any physical problem. By making a systematic dimensional analysis, the dependent variables were determined to be mean oscillating velocity $\overline{u}_{os}$, frequency f, mean pressure drop through the collapsible tube ($\overline{p}_1 - \overline{p}_2$) and the mean downstream transmural pressure at the onset of oscillations ($\overline{p}_2 - \overline{p}_{e,c}$). Similarly the independent parameters were fixed to be h, L, D_o, ρ_w, K_p, $p_{e,c}$, $\overline{u}$, ρ_f and v_f. In the following sections the dependent variables are presented in dimensionless form and their variations with independent non-dimensional terms are expressed.

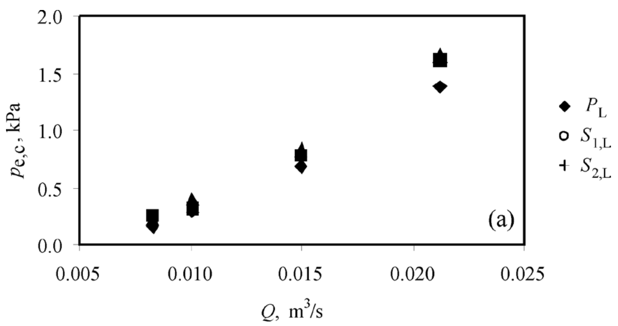


Figure 8. Variation of $p_{e,c}$ with Q to show the effect of L for Penrose tubes

Slika 8. Varijacije $p_{e,c}$ po Q za primjer utjecaja L na Penrose cijevi

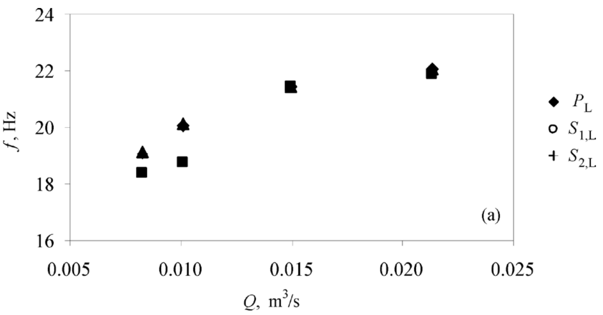


Figure 9. Variation of f with Q to show the effect of L for Penrose tubes

Slika 9. Varijacije f po Q za primjer utjecaja L na Penrose cijevi

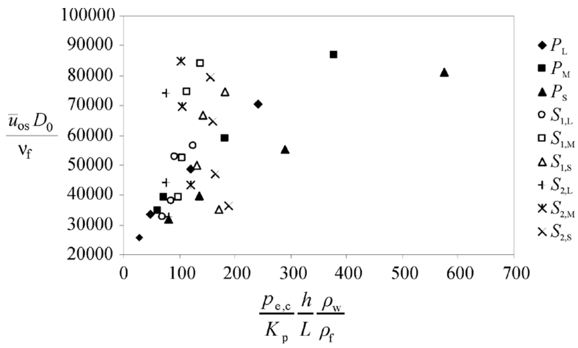


Figure 10. Relationship between $\bar{u}_{os}D_o/\nu_f$ and $p_{e,c}/K_p$, h/L, ρ_w/ρ_f for the test tubes at the onset of oscillations

Slika 10. Odnos između $\bar{u}_{os}D_o/\nu_f$ i $p_{e,c}/K_p$, h/L, ρ_w/ρ_f za ispitne cijevi pri nastanku oscilacija

4.1. Dimensionless mean oscillating velocity

In this section the first dependent term is selected to be $\bar{u}_{os}$ which has been expressed in dimensionless form as $\bar{u}_{os}D_o/\nu_f$. The independent variables are determined to be $p_{e,c}$, h and ρ_w which are expressed non-dimensionally as $p_{e,c}/K_p$, h/L and ρ_w/ρ_f, respectively. Finally the independent dimensionless parameter can be proposed as $\frac{p_{e,c}}{K_p}\frac{h}{L}\frac{\rho_w}{\rho_f}$. It is useful to point out here that the term $\rho_w h/\rho_w L$ defines wall inertia. Pedley and Luo [21] specified that the wall inertia is negligible if the flowing fluid is water; however when fluid is air it should be taken into account since $\rho_w h/\rho_w L$ leads to an independent, high frequency for the latter case. Therefore the effect of wall inertia has already been considered by $\frac{p_{e,c}}{K_p}\frac{h}{L}\frac{\rho_w}{\rho_f}$ term in this study for which air is flowing fluid. The variation of $\bar{u}_{os}D_o/\nu_f$ with $\frac{p_{e,c}}{K_p}\frac{h}{L}\frac{\rho_w}{\rho_f}$ is shown in Figure 10 for the test tubes defined in Table 1. It can be seen in Figure 10 that $\bar{u}_{os}D_o/\nu_f$ is almost linearly changing with $\frac{p_{e,c}}{K_p}\frac{h}{L}\frac{\rho_w}{\rho_f}$ for Penrose tubes regardless of L. However a similar linear relationship between the cited non-dimensional terms is not observed for the silicone rubber tubes. Moreover $20<\frac{p_{e,c}}{K_p}\frac{h}{L}\frac{\rho_w}{\rho_f}<600$ is observed for Penrose tubes, but $80<\frac{p_{e,c}}{K_p}\frac{h}{L}\frac{\rho_w}{\rho_f}<200$ for silicone rubber tubes. Therefore it could be explained that tube material's type is certainly effective on the flow behaviour. It is useful to point out that dimensionless mean oscillating velocity is varying as $25{,}000<\bar{u}_{os}D_o/\nu_f<85{,}000$ strongly depending on the characteristics of the collapsible tube type.

4.2. Dimensionless frequency

The frequency is defined non-dimensionally as fD_o^2/ν_f and the variation of this parameter with $\frac{p_{e,c}}{K_p}\frac{h}{L}\frac{\rho_w}{\rho_f}$ as presented in the previous section is shown in Figure 11. First of all it can be said that there is a serious difference between the behaviour of the data related to Penrose tubes and silicone rubber tubes. The trend of data concerned to silicone rubber tubes is similar to that observed in Figure 10. However the effect of h is considerable for silicone rubber tubes in this case such that there is a range of $825<fD_o^2/\nu_f<1100$ for h=1 mm while $1150<fD_o^2/\nu_f<1500$ is seen for h=2 mm. The trend of the data for Penrose tubes is not similar to the case observed in Figure 10. The data is concentrated in the same band independent of L and it is scattered nearly in an exponential form. It can be comprehended that the dimensionless frequency for Penrose tubes changes as $790<fD_o^2/\nu_f<950$ independent of L. In summary it can be expressed by referring Figure 11 that tube type is effective on fD_o^2/ν_f since the scattering of data is obviously different for silicone rubber and Penrose tubes. The effect of h is clearly prominent for silicone rubber tubes due to the cited range of fD_o^2/ν_f while the effect of L is not sharp in comparison with h. On the other hand L has no considerable influence on the variation of fD_o^2/ν_f with $\frac{p_{e,c}}{K_p}\frac{h}{L}\frac{\rho_w}{\rho_f}$ for Penrose tubes. Furthermore fD_o^2/ν_f is almost constant for Penrose tubes at a value of 925 for the case of $\frac{p_{e,c}}{K_p}\frac{h}{L}\frac{\rho_w}{\rho_f}>200$ regardless of L.

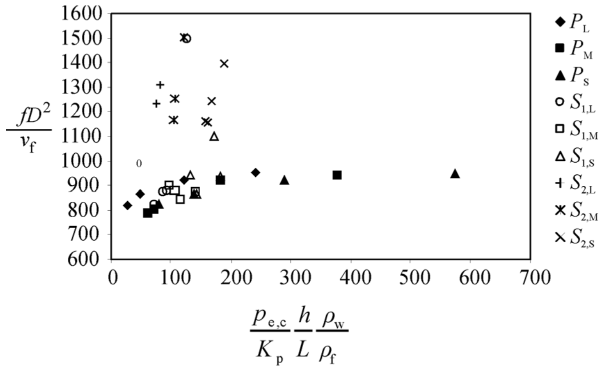


Figure 11. Relationship between fD_o^2/ν_f and $p_{e,c}/K_p$, h/L, ρ_w/ρ_f for the test tubes at the onset of oscillations

Slika 11. Odnos između fD_o^2/ν_f i $p_{e,c}/K_p$, h/L, ρ_w/ρ_f za ispitne cijevi pri nastanku oscilacija

4.3. Dimensionless mean pressure drop through the tube

The next dependent parameter is the pressure drop through collapsible tube $\bar{p}_2 - \bar{p}_1$ which has been defined in dimensionless form as $\sqrt{(\bar{p}_2-\bar{p}_1)/\rho_f}\,(D_o/\nu_f)$. The relationship between $\sqrt{(\bar{p}_2-\bar{p}_1)/\rho_f}\,(D_o/\nu_f)$ and $\frac{p_{e,c}}{K_p}\frac{h}{L}\frac{\rho_w}{\rho_f}$ is presented in Figure 12. It is seen that the data related to Penrose tube and silicone rubber tube shows nearly the similar behaviour such that $\sqrt{(\bar{p}_2-\bar{p}_1)/\rho_f}\,(D_o/\nu_f)$ increases with $\frac{p_{e,c}}{K_p}\frac{h}{L}\frac{\rho_w}{\rho_f}$ for $\frac{p_{e,c}}{K_p}\frac{h}{L}\frac{\rho_w}{\rho_f}<200$. However the behaviour is not valid for $\frac{p_{e,c}}{K_p}\frac{h}{L}\frac{\rho_w}{\rho_f}>200$ considering silicone rubber tube. The magnitude of dimensionless pressure drop value is in the order of 75,000 for $\frac{p_{e,c}}{K_p}\frac{h}{L}\frac{\rho_w}{\rho_f}>200$ associated with Penrose tubes. The effect of L in this case also is not clear in Figure 12 as determined in Figures 8 and 9. The effect of h is apparent such that dimensionless pressure is seen to be in the ranges of $28{,}000<\sqrt{(\bar{p}_2-\bar{p}_1)/\rho_f}\,(D_o/\nu_f)<133{,}000$ for thin-walled silicone rubber tube and $56{,}000<\sqrt{(\bar{p}_2-\bar{p}_1)/\rho_f}\,(D_o/\nu_f)<71{,}000$ for thick-walled silicone rubber tube, namely pressure drop through the collapsible tube increases as the tube wall becomes thinner.

4.4. Dimensionless mean downstream transmural pressure

The last considered dependent variable is the mean downstream transmural pressure $\bar{p}_2 - p_{e,c}$ at the onset of oscillations. It is expressed in terms of dimensionless form

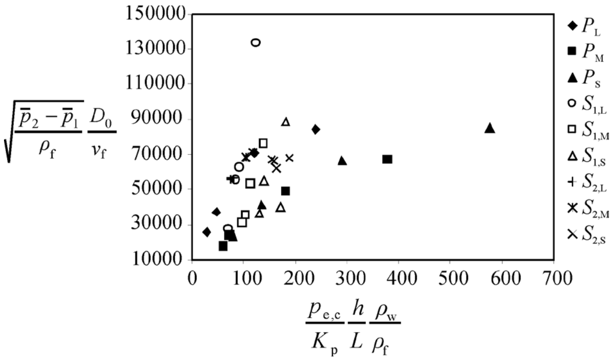


Figure 12. Relationship between $\sqrt{(\bar{p}_2-\bar{p}_1)/\rho_f}\,(D_o/\nu_f)$ and $(p_{e,c}/K_p)(h/L)(\rho_w/\rho_f)$ for the test tubes at the onset of oscillations

Slika 12. Odnos između $\sqrt{(\bar{p}_2-\bar{p}_1)/\rho_f}\,(D_o/\nu_f)$ and $(p_{e,c}/K_p)(h/L)(\rho_w/\rho_f)$ za ispitne cijevi pri nastanku oscilacija

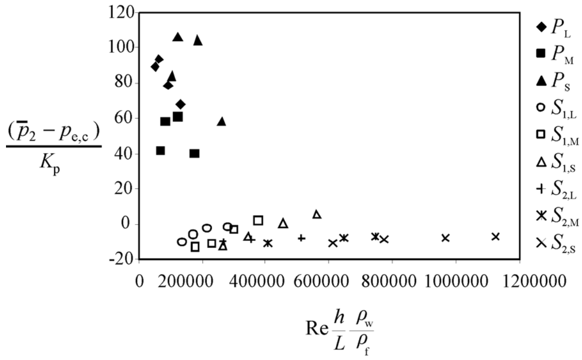


Figure 13. Relationship between $(\bar{p}_2 - p_{e,c})/K_p$ and $\mathrm{Re}(h/L)(\rho_w/\rho_f)$ for the test tubes at the onset of oscillations

Slika 13. Odnos između $(\bar{p}_2 - p_{e,c})/K_p$ and $\mathrm{Re}(h/L)(\rho_w/\rho_f)$ za ispitne cijevi pri nastanku oscilacija

as $(\bar{p}_2 - p_{e,c})/K_p$, namely by dividing to circumferential bending stiffness of the tube. The relationship between non-dimensional terms $(\bar{p}_2 - p_{e,c})/K_p$ and $\mathrm{Re}(h/L)(\rho_w/\rho_f)$ is shown in Figure 13 where Re is Reynolds number of steady flow defined as

$$\mathrm{Re} = \frac{\bar{u}D_o}{\nu_f}, \tag{2}$$

where ν_f is kinematic viscosity of the fluid.

It should be cited at this point that the proposed dimensionless terms have not been selected arbitrarily; in contrary, they were carefully determined by making a dimensional analysis with Buckingham-Pi theorem. Actually, the presented terms cover almost all of the parameters that are directly related to flow and collapsible tube specifications. It is obvious by observing Figure 13 that tube type seriously affects the flow behaviour since the data related to Penrose tube and silicone rubber tube grouped separately. The ranges of dimensionless mean downstream pressure are $40<(\bar{p}_2 - p_{e,c})/K_p<105$ and $-13<(\bar{p}_2 - p_{e,c})/K_p<6$ related with Penrose tube and silicone rubber tubes, respectively. It is evident that $(\bar{p}_2 - p_{e,c})/K_p$ is nearly constant having a value of -8 for the thick-walled silicone rubber tubes independent of $Re(h/L)(\rho_w/\rho_f)$. Nevertheless, $(\bar{p}_2 - p_{e,c})/K_p$ slightly increases with increasing $Re(h/L)(\rho_w/\rho_f)$. Therefore it can once again be emphasized that there is a certain effect of *h* on the flow in collapsible tubes. The effect of *L* is not very clear in Figure 13 in comparison to the effect of *h*.

5. Discussion

It can be remarked here that self-excited oscillations do not occur when the tube collapses, the inner surfaces may contact with each other and steady collapsing state maintains. However this condition is outside scope of the present investigation, since all the cases are focused on the emergence of self-excited oscillations. There should be certainly some effects of upstream and downstream rigid pipes on the flow behaviour; however this issue is outside of the presented investigation's content.

It was demonstrated that frequency of the oscillations could be found by applying FFT on velocity and/or pressure measurement result (Figure 5).The principal experimental results are illustrated by means of the plots supplied from Figure 6 to Figure 9. It is comprehended by interpreting these plots that $p_{e,c}$ and *f* are directly affected due to the tube properties such as *E*, *h*, *L* as well as *Q*. It has been concluded that *f* and particularly $p_{e,c}$ are much more influenced by *E* and *h* in comparison to *L*. In summary it can be suggested that all of these properties should be absolutely considered in collapsible tube flow studies thereby. After obtaining the experimental data at the onset of oscillations for a variety of collapsible tubes, the data was endeavoured to be represented in dimensionless form to remark a general comment on the collapsible tube flow applications. Therefore, a systematic dimensional analysis has been accomplished and eventually relationships between some dimensionless terms comprising almost all of the experimental variables are introduced as shown from Figure 10 to Figure 13. It was determined that $\bar{u}_{os}D_o/\nu_f$, fD_o^2/ν_f, $\sqrt{(\bar{p}_2 - \bar{p}_1)/\rho_f}\,(D_o/\nu_f)$. terms were dependent on $(p_{e,c}/K_p)(h/L)(\rho_w/\rho_f)$. However it was required that variation of $(\bar{p}_2 - p_{e,c})/K_p$ with $Re(h/L)(\rho_w/\rho_f)$ should be considered. One significant factor in the "airflow" through collapsible tubes is the effect of wall inertia defined with $\rho_w h/\rho_f L$ which has already been included through independent term of $(p_{e,c}/K_p)(h/L)(\rho_w/\rho_f)$.

It has been figured out there are certain effects of *E*, *h*, *L* and *Q* on the presented non-dimensional parameters. Figures 8-11 imply that the kind of collapsible tube material is an individual factor which has influence upon flow behaviour. The experimental data related to Penrose tube and silicone rubber tube differ from each other evidently. Furthermore *h* is an effective parameter on the relationships between presented dimensionless expressions. On the other hand the effect of *L* is seen not to be a definite parameter although it somehow affects the oscillating flow.

6. Conclusions

Results of an extensive experimental investigation on airflow in collapsible tubes are presented in this paper by disregarding the topic's relevance to physiology. The experimental data has been acquired when self-excited oscillations originate due to collapse of the tube under applied p_e while air flows through it. It has been verified that both of pressure p_1, p_2 and velocity *u* fluctuate drastically with time in the course of self-excited oscillations. In addition p_2 recognized to be more influenced in comparison with p_1 due to presence of the oscillations (Figure 4).

It can be summarised as the results of such an extensive experimental investigation should be well-illustrative not only for air but also for water flow in collapsible tube applications by considering introduced dimensionless terms. The dimensionless expressions are noteworthy since they comprise various characteristics concerning fluid flow ($\bar{u}_{os}, f, \bar{p}_2 - \bar{p}_1, p_{e,c}, \rho_f, \nu_f$, Re) and tube ($\rho_w$, *h, L*, D_o, *E*, ν). Namely, it can be estimated before any collapsible tube flow experiment that how cited experimental variables may influence the measurements such as frequency, pressure drop through the tube, oscillating flow velocity and downstream transmural pressure.

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