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Near limit behavior of the detonation velocity

John H.S. Lee[1†], Anne Jesuthasan[1] and Hoi Dick Ng[2]

[1]McGill University
Department of Mechanical Engineering
Montreal, QC, Canada

[2]Concordia University
Department of Mechanical and Industrial Engineering
Montreal, QC, Canada

[†]Corresponding Author

John H.S. Lee
McGill University
Department of Mechanical Engineering
817 Sherbrook Street West
Montreal, Quebec, Canada H3A 2K6
Email: john.lee@mcgill.ca
Tel.: (514) 398-6301
Fax: (514) 398-7365

Manuscript accepted for the 34th symposium (International) on Combustion
Colloquium: Detonation, Explosions and Supersonic Combustion

Preferred type of presentation: oral

Total length of paper (method 1): 6198

main text: 2355
references: 402
figure 1 with caption: 302
figure 2 with caption: 471
figure 3 with caption: 452
figure 4 with caption: 473
figure 5 with caption: 300
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by

John H.S. Lee, Anne Jesuthasan and Hoi Dick Ng

Abstract

The behavior of the detonation velocity near the limits is investigated. Circular tubes of diameters 65 mm, 44 mm and 13 mm are used. To simulate a quasi two-dimensional rectangular geometry thin annular channels are also used. The annular channels are formed by a 1.5 m long insert of a smaller diameter tube into the larger outer diameter detonation tube. Premixed mixtures of $C_2H_2 + 2.5O_2 + 70\%Ar$, $CH_4 + 2O_2$ and $C_2H_2 + 5N_2O + 50\%Ar$ are used in the present study. The high argon dilution stoichiometric $C_2H_2 + 2.5O_2$ mixture has a regular cell size and piecewise laminar reaction zone and thus referred to as "stable". The other two mixtures give highly irregular cell pattern and a turbulent reaction zone and are hence, referred to as "unstable" mixtures. Pressure transducers and optical fibers spaced 10 cm apart along the tube are used for pressure and velocity measurements. Cell size of the three mixtures studied is also determined using smoked foils in both the circular tubes and annular channels. The ratio d/λ (representing the number of cells across the tube diameter) is found to be an appropriate sensitivity parameter to characterize the mixture. The present results indicate that well within the limit, the detonation velocity is generally a few percent below the theoretical Chapman-Jouguet (CJ) value. As the limit is approached, the velocity decreases rapidly to a minimum value before the detonation fails. The narrow range of values of d/λ of the mixture where the velocity drops rapidly is found to correspond to the range of values for the onset of single headed spinning detonations. Thus we may conclude that the onset of single headed spin can be used as a criterion for defining the limits. Spinning detonations are also observed near the limits in annular channels.

Keywords: detonation limits; detonation failure.

1. Introduction

Detonation limits is an important fundamental as well as practical problem. However, there is no theory for predicting the limits nor are there meaningful experimental data for the limits as yet. A review of the detonation limit phenomenon together with a comprehensive reference of previous studies is given by Lee [1]. The development of a theory for detonation limits is very difficult as it requires the quantitative description of the complex mechanisms of propagation of cellular detonations. The measurement of the limits experimentally is also difficult due to the fact that the boundary between failure and successful propagation is not precise, but spread over a range of conditions. Existing data on the detonation limits are specific of the apparatus and procedure used. Furthermore an arbitrary criterion is generally required to provide an operational definition of the limits. However, the near limit behavior of the detonation had been well established. As the limits are approached, it is generally observed that the detonation velocity decreases rapidly, the fluctuation in the detonation velocity increases, and the cell size also increases (or equivalently the transverse vibrational frequency of the unstable structure decreases towards the fundamental mode). It appears that further progress can be achieved by studying the near limit behavior of the detonation wave in more detail. In the present study, we report some results on the near limit behavior of the detonation velocity. Although velocity deficit had been extensively investigated in the past [2], these studies are mostly carried out under conditions well within the limits. The aim of these earlier studies is to extrapolate and obtain an “infinite tube diameter velocity” to serve as a reference for comparison with the theoretical Chapman-Jouguet (CJ) values. The present investigation focuses on the near limit regime and the velocity is determined until detonation failure occurs. Although the detonation velocity is not a sensitive parameter that describes the fundamental propagation mechanism, it is compensated by the fact that it can be measured accurately over long distances of propagation of the detonation wave. Parameters like the cell size provide a more direct indication of the unstable detonation structure. However, smoked foils are in general difficult to interpret particularly when the cell pattern is irregular. Cell size measurements often required a certain degree of subjectiveness.

2. Experimental details

The experiments are carried out in circular tube of diameter 65, 44 and 13 mm and thin annular channels of channel thickness (or height) ranging from 3 mm to 9 mm (i.e., 3.175 mm, 6.35 mm and 9.525 mm). The annular channels represent a continuous "quasi two-dimensional" rectangular channel of infinite aspect ratio. The annular channel is formed by inserting a smaller diameter tube into the larger outer detonation tube. Thus, the present study investigates limits in both geometries of circular tubes and "two-dimensional" annular channels. A photograph of the apparatus is shown in Fig. 1. Piezoelectric transducers as well as optical fibers are used for pressure and velocity measurements. Three mixtures (i.e., $C_2H_2 + 2.5O_2 + 70\%Ar$, $CH_4 + 2O_2$, $C_2H_2 + 5N_2O + 50\%Ar$) are used. The first mixture with high argon dilution has been found to give a very regular smoked foil pattern and the detonation showed a piecewise laminar ZND structure [1, 3-5]. The other two mixtures have a more irregular cellular pattern and the reaction zone has a "turbulent like" structure [1, 3-5]. The choice of these two types of so-called "stable" and "unstable" mixtures in the present study is motivated by the fact that their failure mechanisms are found to be different in the critical tube diameter phenomenon [6]. "Stable" detonations in high argon diluted mixtures fail due to excessive curvature of the diffracted shock. For "unstable" detonations, failure results when the instability in the diffracted shock front cannot be developed to re-initiate the detonation [1]. Thus, it would be of interest to study the limit behavior of these two types of mixtures. In the present study, the detonation cell size for the three mixtures used are also measured, and compared with the GALCIT database [7]. Detonation velocity is measured from the time-of-arrival of the detonation at the various optical probe locations (spaced 10 cm apart along the detonation tube). A local velocity (from two adjacent probes) as well as an overall averaged velocity (determined from the slope of the detonation trajectory) can be obtained. Well within the limits, the fluctuations in the local velocity are small and the averaged local velocity agrees with the global averaged velocity in general. However near the limits, the fluctuations of the local velocity become large. Close to failure, the fluctuation of the local velocity can be quite significant and it is no longer meaningful to obtain a global averaged value of the velocity. The velocity reported in the present study is the averaged velocity obtained from the slope of the detonation trajectory. The local velocity fluctuations are only used to provide a qualitative idea of the near limit behavior. Detonation failure is generally indicated by a continuous decay of the detonation past the minimum velocity. The minimum velocity just prior to failure is obtained when the trajectory still indicates a self-sustained detonation without decay.

3. Results and discussion

In the present study the limits are approached by a reduction in the initial pressure for a given mixture composition and a given tube diameter. A reduction in the initial pressure decreases the sensitivity of the mixture and is equivalent to an increase in the detonation cell size. Rather than the cell size alone, it is found that the ability of a detonation to propagate in a tube depends on the ratio d/λ, i.e., the number of cells across the tube diameter [8-11]. Although an attempt was also made in [12] to try various parameters for characterization, d/λ still remains the most appropriate sensitivity parameters to bring the results together. Indeed, the effect of boundary conditions and the propagation limits should be governed by the tube dimension and with the importance of instability in the near-limit conditions, this tube diameter should be related to the length scale of the detonation structure itself characterized by λ.

In the present results, well within the limit, $d/\lambda >> 1$ and d/λ decreases as the limits are approached. The velocity versus d/λ for $C_2H_2 + 2.5O_2 + 70\%Ar$ is shown in Fig. 2 for the circular tubes. Well within the limits (large values of d/λ) the velocity is observed to be close to the theoretical CJ values with a typical velocity deficit of a few percent. However as the limits are approached, the detonation velocity decreases rapidly to a minimum until no steady detonation can be obtained past the minimum value. For $C_2H_2 + 2.5O_2 + 70\%Ar$ mixture, the minimum steady velocity obtained is about $V/V_{CJ} \approx 0.85$. The rapid decrease in the detonation velocity corresponds to the range of $d/\lambda \approx 0.3$ which corresponds to the range of d/λ for the onset of spinning detonation of $0.318 \leq d/\lambda \leq 0.5$. For $CH_4 + 2O_2$, the velocity versus d/λ is shown in Fig. 3. The velocity shows a stronger dependence of tube diameter for $CH_4 + 2O_2$ than for $C_2H_2 + 2.5O_2 + 70\%Ar$ (see Fig. 2). Again well within the limit, $V/V_{CJ} \approx 0.97$ and the velocity drops sharply as the limiting value of d/λ is reached. The drop in detonation velocity is more "precipitous" in $CH_4 + 2O_2$ than for "stable" detonations in $C_2H_2 + 2.5O_2 + 70\%Ar$. The limiting values of d/λ for the three tubes also compare well with the values for the onset of single headed spin of $0.318 \leq d/\lambda \leq 0.5$.

For $C_2H_2 + 5N_2O + 50\%Ar$, the velocity results are shown in Fig. 4. Well within the limit, $V/V_{CJ} \approx 0.97$ but the decrease in velocity as the limits are approached is less rapid than the previous mixtures. Also the minimum velocity when the detonation fails is of the order of $V/V_{CJ} \approx 0.87$, relatively higher than the corresponding values for $CH_4 + 2O_2$ and $C_2H_2 + 2.5O_2 + 70\%Ar$.

For the annular channels, smoked foil records indicate a single headed spin based on the circumference of the annular channel (Fig. 5) is also observed prior to failure. This is a surprising result since in a two-dimensional channel, one would expect failure to corresponds to a "zig-zag" detonation (equivalent to a spinning detonation in a round tube) as observed by Dove and Wagner [13]. The existence of a single headed spin in the annular channel indicates a certain "robustness" of the detonation which always tends to seek the larger length scale to execute a lower frequency unstable mode to continue to maintain self-sustained propagation. Failure would have occurred much sooner if based on the "zig-zag" mode governed by the smaller dimension of the channel thickness.

Thus even for annular channels, we use the same parameter d/λ rather than w/λ (where w is the thickness of the annular channel). Figure 6 shows the velocity variation with d/λ for $C_2H_2 + 2.5O_2 + 70\%Ar$. The minimum velocity prior to failure is now lower than the corresponding values for round tubes. This is perhaps a result of the wall boundary layer effect being more prominent for thin annular channels. For instance, from [14-16], the displacement thickness due to the wall boundary layer developed behind a shock can be estimated by $\delta \sim 0.22x^{0.8}\left(\mu/\rho u\right)^{0.2}$ where x is the distance behind the leading shock, μ the gas viscosity, ρ the density and u the gas velocity in the shock frame of reference. Near the limit condition, the overall detonation reaction length approximated by the ideal ZND model is of the order of ~ 1 mm. In the case of the annular channels, the boundary layer is becoming comparable to the channel width of few millimeters thickness and its effect would be more prominent than in a round tube of diameter of centimeters. Equivalently to the work by Manzhalei [17] which studied detonation propagation in capillary tubes with small diameter d, passed the spinning and multiple-cells front detonation, a galloping regime is observed and at lower limit when the thickness of the boundary layer is $\sim 0.1d$, a low-speed detonation regime of gases also exists. Low speed and galloping detonation regimes are often not observed in a tube with larger diameter where the transitional section may occupy a large portion of the tube length. This low velocity regime with limiting detonation speed of $V/V_{CJ} \sim 0.7$ is also observed in [18] for the stoichiometric $C_2H_2 + 2.5O_2$ mixture with the smallest diameter circular tube of 1.8 mm. Also found in the present results is that the d/λ values at the limit are of the order of the range for the onset of single headed spin of $0.318 \leq d/\lambda \leq 0.5$. The corresponding velocity plot for $CH_4 + 2O_2$ for annular channels is also illustrated in Fig. 7. The minimum velocity is found to be much lower than that of $C_2H_2 + 2.5O_2$ + 70%Ar. The limiting values for d/λ also agree with the range for the onset of single headed spin of $0.318 \leq d/\lambda \leq 0.5$.

Similar results for the velocity plot for $C_2H_2 + 5N_2O$ + 50%Ar for annular channels is given in Fig. 8. The limits correspond also to the onset of spinning detonation in the range of $0.318 \leq d/\lambda \leq 0.5$.

4. Conclusion

It is found that the detonation velocity decreases rapidly as the limits are approached. The velocity decreases to a minimum value before the detonation fails. When the detonation is within the limits the velocity is typically a few percent lower than the theoretical Chapman-Jouguet value. In the larger diameter tubes (65 mm, 44 mm), the velocity decrease is sufficiently rapid to permit the limit condition to be defined by the narrow range of the sensitivity parameter d/λ. In small diameter tube (13 mm), the velocity decrease is less rapid due to more significant wall effects. It is found that the ratio d/λ provides a good measurement for the ability of the detonation to propagate. The ratio d/λ represents the number of detonation cells across the tube diameter and it agrees with the well established fact that within the limit, the cells are small compared to the tube diameter and near the limit the value of $d/\lambda \leq 1$. The present results also show that the limits correspond to the onset of single headed spinning detonation, a criterion suggested previously by Gordon et al. [19], Moen et al. [20] and Kogarko and Zel'dovich [21]. Even for thin annular channels, it is found that the limits also correspond to the onset of single headed spinning detonation around but based on the larger length scale of the circumference of thin annular channels than the thickness of the channel. This is in contrast to the expected result that the channel thickness being a much smaller length scale than the circumference, should govern the onset of the lowest mode of a so-called "zig-zag" detonation. Results for the annular channel indicate that limits for annular channel also correspond to the onset of single headed spinning detonation as in round tubes. In retrospect this may not be too surprising a result since for a single headed spinning detonation in a round tube, the strong Mach stem of the spin head is located only near the tube wall with much of the interior of the tube cross section playing a minor role. For thin annular channels, the wall effects are more prominent and the drop in detonation velocity as the limit is approached is slightly less rapid than for round tubes. Finally, that the disappearance of spinning detonation or the transverse vibrational modes corresponds to the failure of the detonation indicates the essential role of instability in maintaining self-sustained propagation of the detonation wave. Further progress requires a more detailed investigation of the structure of the detonation near its failure to reveal the role played by instability in the propagation of the detonation.

Acknowledgments

This work is supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Fonds de Recherche du Québec – Nature et Technologies (FQRNT).

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Figure Captions

Fig. 1 Photograph of the experimental apparatus

Fig. 2 Variation of normalized detonation velocity with d/λ in $C_2H_2 + 2.5O_2 + 70\%Ar$ mixture in circular tubes.

Fig. 3 Variation of normalized detonation velocity with d/λ in $CH_4 + 2O_2$ mixture in circular tubes.

Fig. 4 Variation of normalized detonation velocity with d/λ in $C_2H_2 + 5N_2O + 50\%Ar$ mixture in circular tubes.

Fig. 5 Smoked foil records of a spinning detonation ($C_2H_2 + 5N_2O + 50\%Ar$, $p_0 = 3.5$ kPa, 6.35 mm annular channel).

Fig. 6 Variation of normalized detonation velocity with d_{tube}/λ in $C_2H_2 + 2.5O_2 + 70\%Ar$ mixture in annular channels.

Fig. 7 Variation of normalized detonation velocity with d_{tube}/λ in $CH_4 + 2O_2$ mixture in annular channels.

Fig. 8 Variation of normalized detonation velocity with d_{tube}/λ in $C_2H_2 + 5N_2O + 50\%Ar$ mixture in annular channels.

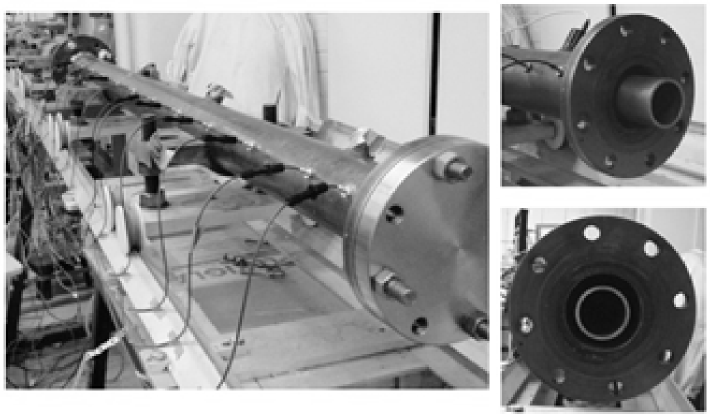


Fig. 1

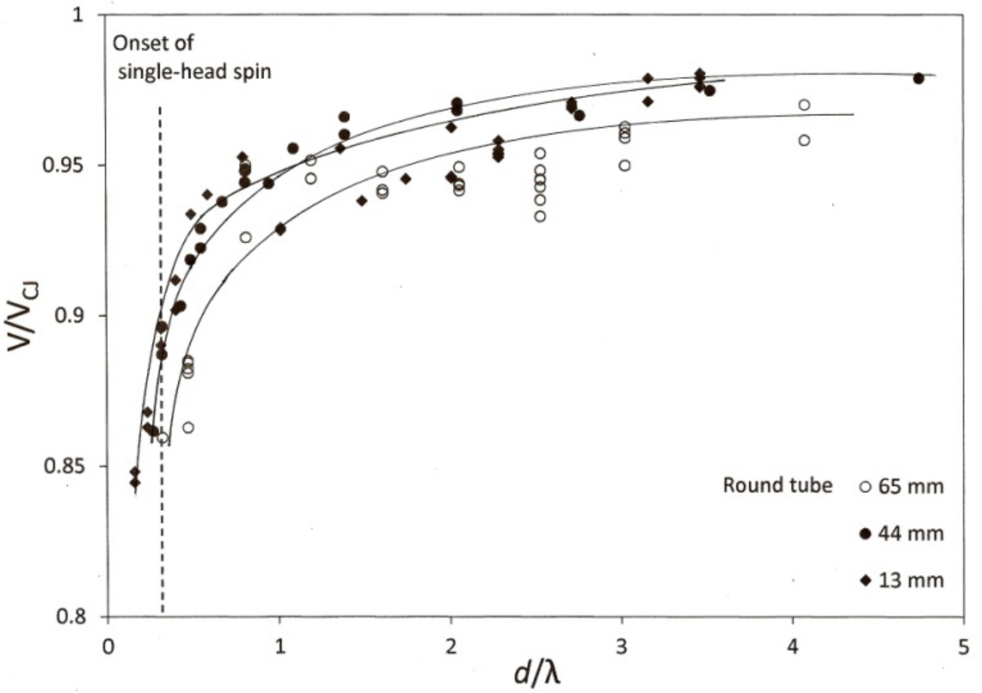
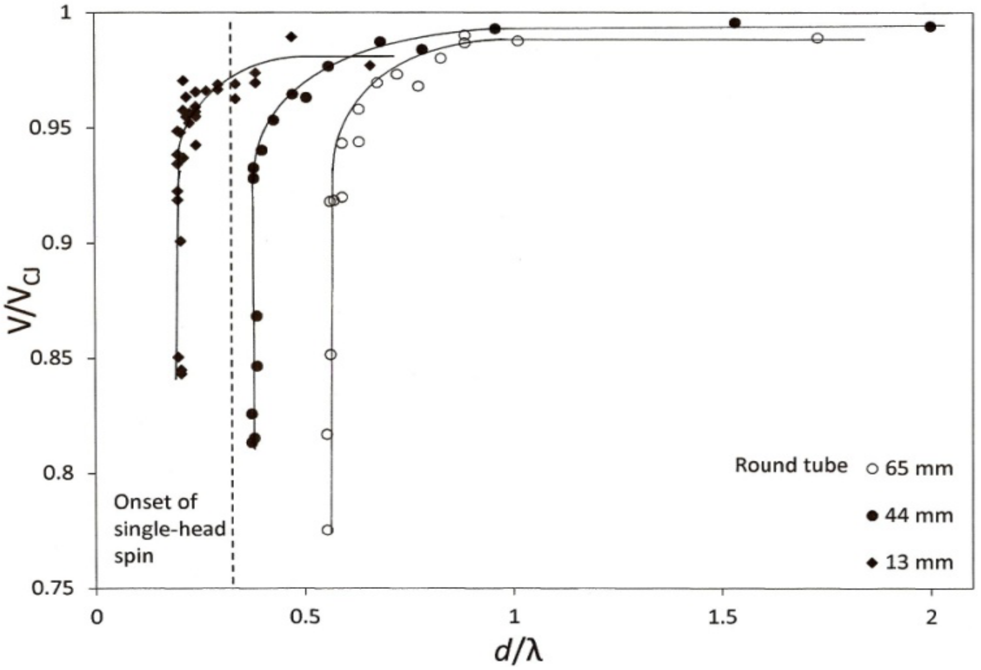

Onset of
single-head spin
1
0.95
0.9
0.85
0.8
0
1
2
3
4
5
V/V_{CJ}
d/λ
Round tube
○ 65 mm
● 44 mm
◆ 13 mm

Fig. 2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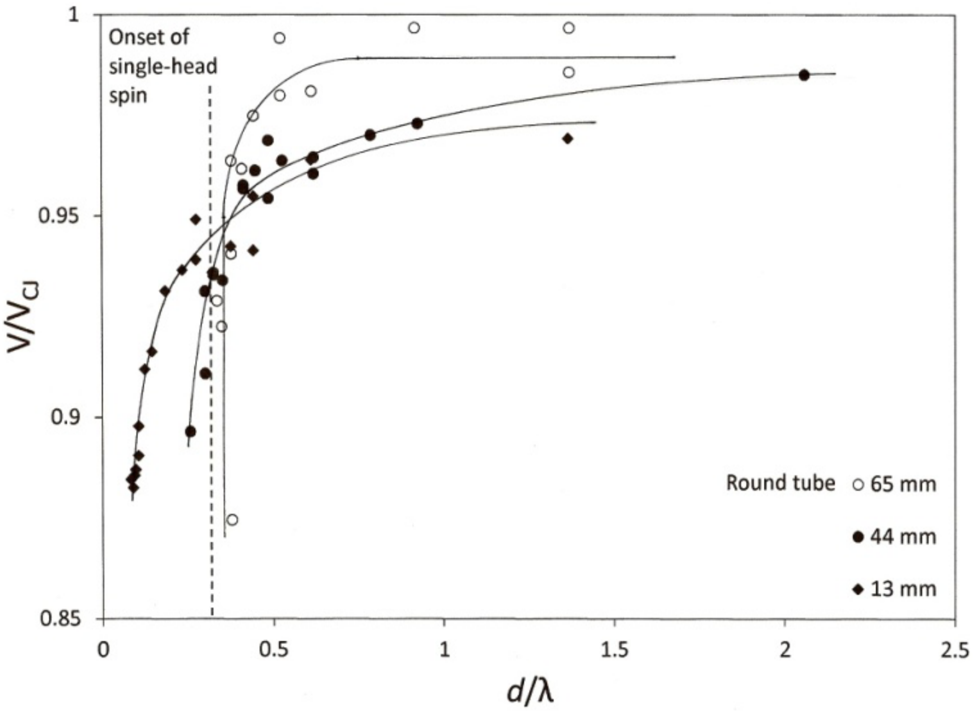
0.95
0.9
0.85
0.8
0.75
V/V_{CJ}
0
0.5
1
1.5
2
d/λ
Onset of single-head spin
Round tube ○ 65 mm
● 44 mm
◆ 13 mm

Fig. 3



1
0.95
0.9
0.85
V/V$_{CJ}$
0
0.5
1
1.5
2
2.5
d/λ
Onset of
single-head
spin
Round tube ○ 65 mm
● 44 mm
◆ 13 mm

Fig. 4

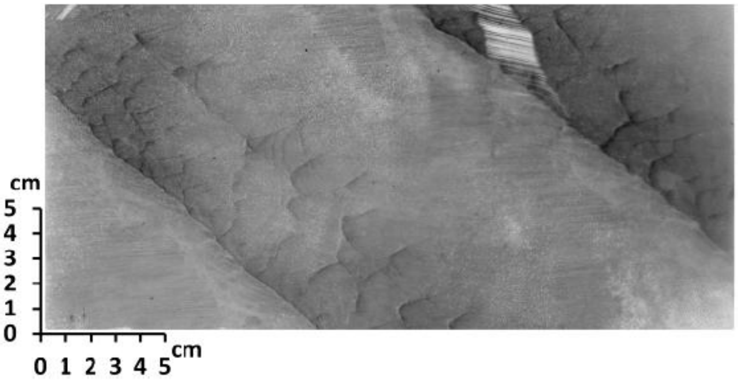
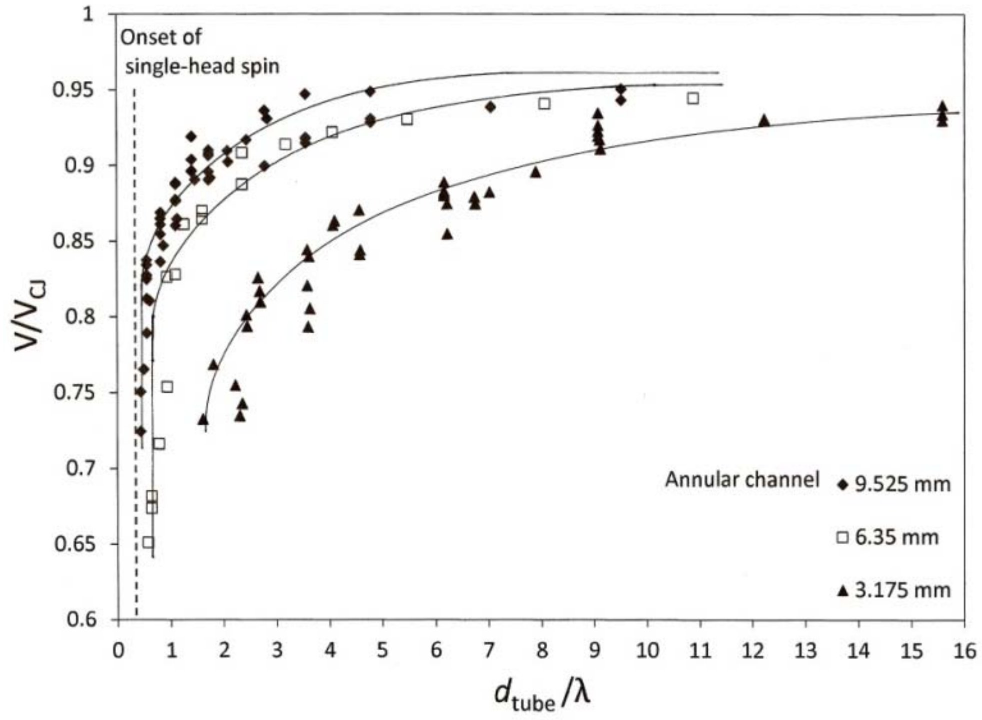


Fig. 5


Onset of single-head spin
V/V$_{CJ}$
d_{tube}/λ
Annular channel
◆ 9.525 mm
□ 6.35 mm
▲ 3.175 mm
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
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4
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16

Fig. 6

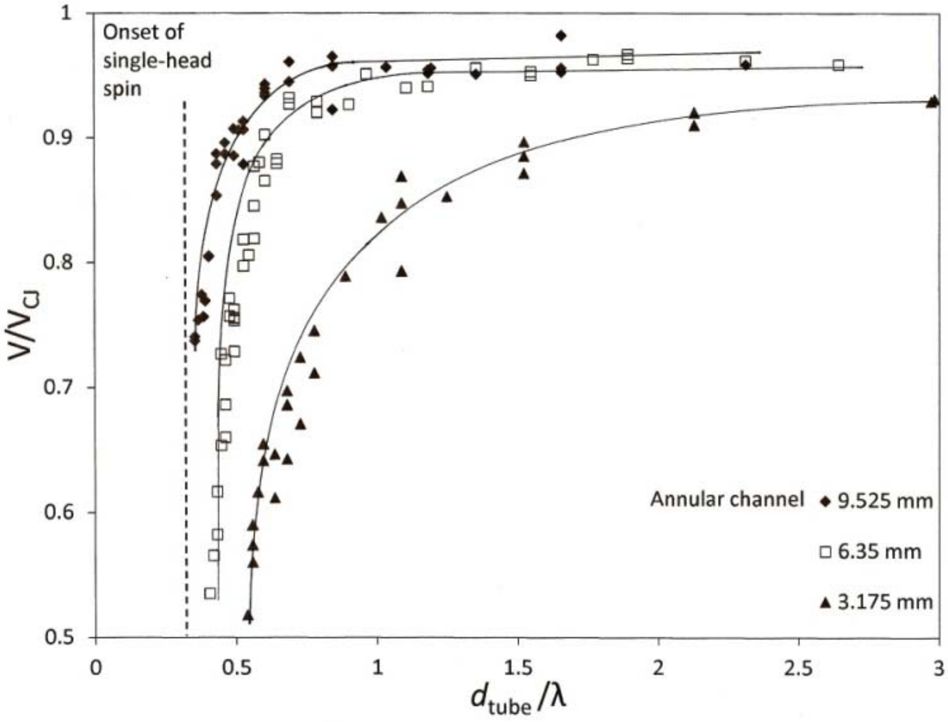
Onset of
single-head
spin
V/V$_{CJ}$
1
0.9
0.8
0.7
0.6
0.5
0
0.5
1
1.5
2
2.5
3
d_{tube}/λ
Annular channel ◆ 9.525 mm
□ 6.35 mm
▲ 3.175 mm

Fig. 7

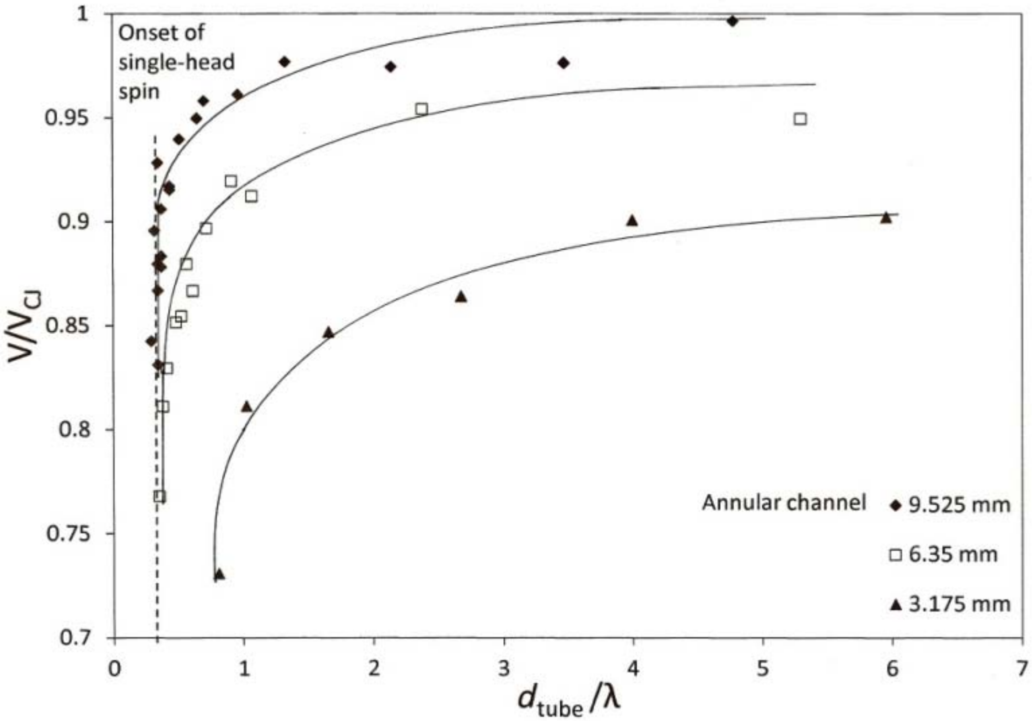
Onset of
single-head
spin
1
0.95
0.9
0.85
0.8
0.75
0.7
V/V$_{CJ}$
0
1
2
3
4
5
6
7
d_{tube}/λ
Annular channel
◆ 9.525 mm
□ 6.35 mm
▲ 3.175 mm

Fig. 8