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Measurement of fluid flow in closed conduits — Guidelines on the effects of flow pulsations on flow-measurement instruments

Mesurage du débit des fluides dans les conduites fermées — Lignes directrices relatives aux effets des pulsations d'écoulement sur les instruments de mesure de débit

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Foreword

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This fourth edition of ISO/TR 3313:2018 is a technical revision of ISO/TR 3313:1998, which was withdrawn in 2013.

Measurement of fluid flow in closed conduits — Guidelines on the effects of flow pulsations on flow-measurement instruments

1 Scope

This document defines pulsating flow, compares it with steady flow, indicates how it can be detected, and describes the effects it has on orifice plates, nozzles or Venturi tubes, turbine and vortex flowmeters when these devices are being used to measure fluid flow in a pipe. These particular flowmeter types feature in this document because they are amongst those types most susceptible to pulsation effects. Methods for correcting the flowmeter output signal for errors produced by these effects are described for those flowmeter types for which this is possible. When correction is not possible, measures to avoid or reduce the problem are indicated. Such measures include the installation of pulsation damping devices and/or choice of a flowmeter type which is less susceptible to pulsation effects.

This document applies to flow in which the pulsations are generated at a single source which is situated either upstream or downstream of the primary element of the flowmeter. Its applicability is restricted to conditions where the flow direction does not reverse in the measuring section but there is no restriction on the waveform of the flow pulsation. The recommendations within this document apply to both liquid and gas flows although with the latter the validity might be restricted to gas flows in which the density changes in the measuring section are small as indicated for the particular type of flowmeter under discussion.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
steady flow
flow in which parameters such as velocity, pressure, density and temperature do not vary significantly enough with time to prevent measurement to within the required uncertainty of measurement

3.2
pulsating flow
flow in which the flowrate in a measuring section is a function of time but has a constant mean value when averaged over a sufficiently long period of time, which depends on the regularity of the pulsation

Note 1 to entry: Pulsating flow can be divided into two categories:

— periodic pulsating flow;

— randomly fluctuating flow.

Note 2 to entry: For further amplification of what constitutes steady or pulsating flow see 5.1 and 5.2.

Note 3 to entry: Unless otherwise stated in this document the term “pulsating flow” is always used to describe periodic pulsating flow.

4 Symbols and subscripts

4.1 Symbols

A	area
A_d	area of the throat of a Venturi nozzle
A_R	turbine blade aspect ratio
a_r, b_r, c_r	amplitude of the r^th harmonic component in the undamped or damped pulsation
B	bf_p/q_V, dimensionless dynamic response parameter
b	turbine flowmeter dynamic response parameter
C	turbine blade chord length
C_c	contraction coefficient
C_D	discharge coefficient
C_v	velocity coefficient
c	speed of sound
D	internal diameter of the tube
d	throat bore of orifice, nozzle or Venturi tube
E_R	residual error in time-mean flowrate when calculated using the quantity $\sqrt{\Delta p}$
E_T	total error in the time-mean flowrate
f	turbine flowmeter output signal, proportional to volumetric flowrate
f_p	pulsation frequency
f_r	resonant frequency
f_v	vortex-shedding frequency
H	harmonic distortion factor
Ho	Hodgson number
I	moment of inertia
I_R, I_F	moments of inertia of turbine rotor and fluid contained in rotor envelope respectively
k/D	relative roughness of pipe wall
L	turbine blade length
L_e	effective axial length
l	impulse line length for differential pressure (DP) measurement device

$m = \beta^2$	orifice or nozzle throat to pipe area ratio
N	number of blades on turbine rotor
p	pressure (absolute)
q_m	mass flowrate
q_V	volume flowrate
R	turbine blade mean radius
Re	Reynolds number
r_h, r_t	turbine blade hub and tip radii respectively
Sr	Strouhal number
Sr_d	Strouhal number based on orifice diameter
t	time
t_b	turbine blade thickness
U	axial bulk-mean velocity
U_d	bulk-mean velocity based on orifice diameter
V	volume
X	temporal inertia term for short pulsation wavelengths
α	$U'_\mathrm{RMS} / \overline{U}$
β	orifice or nozzle throat to pipe diameter ratio
γ	ratio of specific heat capacities (c_p/c_V)
Δp	differential pressure
$\Delta\varpi$	pressure loss
ε_ss	expansibility factor for steady flow conditions
η	blade “airfoil efficiency”
θ	phase angle
κ	isentropic exponent (= γ for a perfect gas)
μ	damping response factor (see 6.1.4.1.3)
ρ	fluid density
ρ_b	turbine blade material density
$\tau = p_2/p_1$	pressure ratio

φ	maximum allowable uncertainty in the indicated flowrate due to pulsation at the flowmeter
ψ	maximum allowable relative error
$\omega = 2\pi f_p$	angular pulsation frequency

4.2 Subscripts and superscripts

o	pulsation source
p	measured under pulsating flow conditions, possibly damped
po	measured under pulsating flow conditions before damping
RMS	root mean square
ss	measured under steady flow conditions
$\bar{}$ (over-bar)	the time-mean value
1,2	measuring sections
'	fluctuating component about mean value, e.g. U'

5 Description and detection of pulsating flow

5.1 Nature of pipe flows

Truly steady pipe flow is only found in laminar flow conditions which can normally only exist when the pipe Reynolds number, *Re*, is below about 2 000. Most industrial pipe flows have higher Reynolds numbers and are turbulent which means that they are only statistically steady. Such flows contain continual irregular and random fluctuations in quantities such as velocity, pressure and temperature. Nevertheless, if the conditions are similar to those which are typical of fully developed turbulent pipe flow and there is no periodic pulsation, the provisions of such standards as ISO 5167 (all parts) apply.

The magnitude of the turbulent fluctuations increases with pipe roughness, and this is one of the reasons why ISO 5167 (all parts) stipulates a maximum allowable relative roughness, k/D, of the upstream pipe for each type of primary device covered by ISO 5167 (all parts).

ISO 5167 (all parts), however, cannot be applied to flows which contain any periodic flow variation or pulsation.

5.2 Threshold between steady and pulsating flow

5.2.1 General

If the amplitude of the periodic flowrate variations is sufficiently small there should not be any error in the indicated flowrate greater than the normal measurement uncertainty. It is possible to define amplitude thresholds for both differential pressure (DP) type flowmeters and turbine flowmeters without reference to pulsation frequency. It is also possible to do this for vortex flowmeters but extreme caution is necessary if even the smallest amplitude is known to be present in the flow.

For DP-type flowmeters, the threshold is relevant when slow-response DP cells are being used. In the case of turbine flowmeters, the threshold value is relevant when there is any doubt about the ability of the rotor to respond to the periodic velocity fluctuations. In the case of a vortex flowmeter the pulsation frequency relative to the vortex-shedding frequency is a much more important parameter than the velocity pulsation amplitude.

5.2.2 Differential pressure (DP) type flowmeters

The threshold can be defined in terms of the velocity pulsation amplitude such that the flow can be treated as steady if

$$\frac{U'_{RMS}}{\bar{U}} \leq 0{,}05 \tag{1}$$

where U is the instantaneous bulk-mean axial velocity such that

$$U = U' + \bar{U} \tag{2}$$

where

U' is the periodic velocity fluctuation;

$\bar{U}$ is the time-mean value.

The threshold in terms of the equivalent DP pulsation amplitude is

$$\frac{\Delta p'_{p,RMS}}{\overline{\Delta p_p}} \leq 0{,}10 \tag{3}$$

where Δp_p is the instantaneous differential pressure across the tappings of the primary device such that

$$\Delta p_p = \overline{\Delta p_p} + \Delta p'_p \tag{4}$$

where

$\overline{\Delta p_p}$ is the time-mean value;

$\Delta p'_p$ is the periodic differential pressure fluctuation.

To determine the velocity pulsation amplitude it is necessary to use one of the techniques described in 5.5 such as laser Doppler or thermal anemometry. To determine the DP pulsation amplitude it is necessary to use a fast-response DP sensor and to observe the rules governing the design of the complete secondary instrumentation system as described in 6.1.3.

Theoretical considerations are covered in Annex A.

5.2.3 Turbine flowmeters

At a given velocity pulsation amplitude a turbine flowmeter tends to read high as the frequency of pulsation increases and exceeds the frequency at which the turbine rotor can respond faithfully to the velocity fluctuations. The positive systematic error reaches a plateau value depending on the amplitude and thus the threshold amplitude can be defined such that the resulting maximum systematic error is still within the general measurement uncertainty. For example, if the overall measurement uncertainty is greater than or equal to 0,5 % then it can be assumed that a systematic error due to pulsation of 0,1 % or less has negligible effect on the overall measurement uncertainty.

The velocity amplitude of sinusoidal pulsation, $U'_{\mathrm{RMS}} / \overline{U}$, that produces a systematic error of 0,1 % in a turbine flowmeter is 3,5 %. Thus the threshold for sinusoidal pulsation is given by

$$\frac{U'_{\mathrm{RMS}}}{\overline{U}} \leq 0{,}035 \quad (5)$$

Techniques such as laser Doppler and thermal anemometry can be used to determine the velocity pulsation amplitude. If the flowmeter output is a pulse train at the blade passing frequency and if the rotor inertia is known, then signal analysis can be used to determine the flow pulsation amplitude as described in 6.2.

5.2.4 Vortex flowmeters

A vortex flowmeter is subject to very large pulsation errors when the vortex-shedding process locks in to the flow pulsation. There is a danger of this happening when the pulsation frequency is near the vortex-shedding frequency. At a sufficiently low amplitude, locking-in does not occur and flow-metering errors due to pulsation are negligible. This threshold amplitude, however, is only about 3 % of the mean velocity and is comparable to the velocity turbulence amplitude. The consequences of not detecting the pulsation or erroneously assuming the amplitude is below the threshold can be very serious. This issue is discussed further in 6.3.

5.3 Causes of pulsation

Pulsation occurs commonly in industrial pipe flows. It might be generated by rotary or reciprocating positive displacement engines, compressors, blowers and pumps. Rotodynamic machines might also induce small pulsation at blade passing frequencies. Pulsation can also be produced by positive-displacement flowmeters. Vibration, particularly at resonance, of pipe runs and flow control equipment is also a potential source of flow pulsation, as are periodic actions of flow controllers, e.g. valve "hunting" and governor oscillations. Pulsation might also be generated by flow separation within pipe fittings, valves, or rotary machines (e.g. compressor surge).

Flow pulsation can also be due to hydrodynamic oscillations generated by geometrical features of the flow system and multiphase flows (e.g. slugging). Vortex shedding from bluff bodies such as thermometer wells, or trash grids, or vortex-shedding flowmeters fall into this category. Self-excited flow oscillations at tee-branch connections are another example.

5.4 Occurrence of pulsating flow conditions in industrial and laboratory flowmeter installations

In industrial flows, there is often no obvious indication of the presence of pulsation, and the associated errors, because of the slow-response times and heavy damping of the pressure and flow instrumentation commonly used. Whenever factors such as those indicated in 5.3 are present, there is the possibility of flow pulsation occurring. It should also be appreciated that pulsation can travel upstream as well as downstream and thus possible pulsation sources could be on either side of the flowmeter installation. However, amplitudes might be small and, depending on the distance from pulsation source to flowmeter, might be attenuated by compressibility effects (in both liquids and gases) to undetectable levels at the flowmeter location. Pulsation frequencies range from fractions of a hertz to a few hundred hertz; pulsation amplitudes relative to mean flow vary from a few percent to 100 % or larger. At low percentage amplitudes the question arises of discrimination between pulsation and turbulence.

Flow pulsation can be expected to occur in various situations in petrochemical and process industries, natural gas distribution flows at end-user locations and internal combustion engine flow systems. Flow-metering calibration systems might also experience pulsation arising from, for example, rotodynamic pump blade passing effects and the effects of rotary positive-displacement flowmeters.

5.5 Detection of pulsation and determination of frequency, amplitude and waveform

5.5.1 General

If the presence of pulsation is suspected then there are various techniques available to determine the flow pulsation characteristics.

5.5.2 Characteristics of the ideal pulsation sensor

The ideal sensor would be non-intrusive, would measure mass flowrate, or bulk flow velocity, and would have a bandwidth from decihertz to several kilohertz. The sensor would respond to both liquids and gases and not require any supplementary flow seeding. The technique would not require optical transparency or constant fluid temperature. The sensor would be uninfluenced by pipe wall material, transparency or thickness. The device would have no moving parts, its response would be linear, its calibration reliable and unaffected by changes in ambient temperature.

5.5.3 Non-intrusive techniques

5.5.3.1 Optical: laser Doppler anemometry (LDA)

This technology is readily available, but expensive. Measurement of point velocity on the tube axis allows an estimate only of bulk flow pulsation amplitude and waveform but, for constant frequency pulsation, accurate frequency measurements can be made. Optical access to an optically transparent fluid is either by provision of a transparent tube section, or insertion of a probe with fibre-optic coupling. With the exception of detecting low frequency pulsation, supplementary seeding of the flow would probably be required to produce an adequate bandwidth. LDA characteristics are comprehensively described in Reference [2].

5.5.3.2 Acoustic: Doppler shift; transit time

Non-intrusive acoustic techniques are suitable for liquid flows only, because for gas flows there is poor acoustic-impedance match between the pipe wall and flowing gases. For the externally mounted transmitter and receiver, usually close-coupled to the tube wall, an acoustically transparent signal path is essential. The Doppler shift technique might require flow seeding to provide adequate scattering. Instruments for point velocity measurements are available which, as for the LDA, provide only an estimate of bulk flow pulsation amplitude and waveform. Moreover, Doppler-derived “instantaneous” full-velocity profile instruments[3] allow much closer estimates of bulk flow pulsation characteristics. Transit-time instruments measure an average velocity, most commonly along a diagonal path across the flow. All acoustic techniques are limited in bandwidth by the requirement that reflections from one pulse of ultrasound should decay before transmission of the next pulse. Many commercial instruments do not provide the signal processing required to resolve unsteady flow components. An investigation by Hakansson[4] on a transit time, intrusive-type ultrasonic flowmeter for gases subjected to pulsating flows showed that only small shifts in the calibration took place and that these were attributable to the changing velocity profile.

5.5.3.3 Electromagnetic flowmeters

When the existing flowmeter installation is an electromagnetic device, then, if it is of the pulsed d.c. field type (likely maximum d.c. pulse frequency a few hundred hertz), there is the capability to resolve flow pulsation up to frequencies approximately five times below the excitation frequency. This technique is only suitable for liquids with an adequate electrical conductivity. It provides a measure of bulk flow pulsation, although there is some dependence upon velocity profile shape[5].

5.5.4 Insertion devices

5.5.4.1 Thermal anemometry

The probes used measure point velocity, and relatively rugged (e.g. fibre-film) sensors are available for industrial flows. These probes generally have an adequate bandwidth, but the amplitude response is inherently non-linear. As with other point velocity techniques, pulsation amplitude and waveform can only be estimated. Estimates of pulsation velocity amplitude relative to mean velocity may be made without calibration. The RMS value of the fluctuating velocity component can be determined by using a true RMS flowmeter to measure the fluctuating component of the linearized anemometer output voltage. Mean-sensing RMS flowmeters should not be used as these only read correctly for sinusoidal waveforms. Accurate frequency measurements from spectral analysis can be made for constant frequency pulsation.

Applications are limited to clean, relatively cool, non-flammable and non-hostile fluids. Cleanness of flow is very important; even nominally clean flows can result in rapid fouling of probes with a consequent dramatic loss of response. A constant temperature flow is desirable although a slowly varying fluid temperature can be accommodated.

5.5.4.2 Other techniques

Insertion versions of both acoustic and electromagnetic flowmeters are available. Transit-time acoustic measurements can be made in gas flows when the transmitter and receiver are directly coupled to the flow[6], although this might require a permanent insertion. Again there is the limitation of a lack of commercially available instrumentation with the necessary signal processing to resolve time-varying velocity components.

Insertion electromagnetic flowmeters are not widely available and are subject to the same bandwidth limitations as the tube version, due to the maximum sampling frequency of the signal.

5.5.5 Signal analysis on existing flowmeter outputs: software tools

5.5.5.1 Orifice plate with fast-response DP sensor

A fast-response secondary measurement system is capable of correctly following the time-varying pressure difference produced by the primary instrument provided the rules given in 6.1.3.2 can be followed. In principle, a numerical solution of the pressure difference/flow relationship derived from the quasi-steady temporal inertia model, Formula (A.11), would then provide an approximation to the instantaneous flow. The square-root error would not be present, although other measurement uncertainties (e.g. C_D variations, compressibility effects) produced by the pulsation would be. Successive numerical solutions would then provide an approximation to the flow as a function of time and, hence, amplitude and waveform information. Frequency information can be determined directly from the measured pressure difference. At the time of publication of this document, there is no software tool described for this implementation.

However, the maximum probable value of $q'_{V\mathrm{o,RMS}}$ can be approximately inferred from a measurement of $\Delta p'_{\mathrm{po,RMS}}$ using one of the following two inequalities:

$$\frac{q'_{V\mathrm{o,RMS}}}{\overline{q_V}} \leq \frac{1}{2} \frac{\Delta p'_{\mathrm{po,RMS}}}{\Delta p_{\mathrm{ss}}} \tag{6}$$

$$\frac{q'_{V\text{o,RMS}}}{\overline{q_V}} \le \left\{ \frac{2}{1+[1-(\Delta p'_{\text{po,RMS}}/\overline{\Delta p}_{\text{po}})]^{1/2}} - 1 \right\}^{1/2} \tag{7}$$

where

$\Delta p'_{\text{po,RMS}}$ is the r.m.s. value of the fluctuating component of the differential pressure across the primary element measured using a fast-response secondary measurement system;

Δp_{ss} is the differential pressure that would be measured across the primary element under steady flow conditions with the same time-mean flowrate;

$\overline{\Delta p}_{\text{po}}$ is the time-mean differential pressure that would be measured across the primary element under undamped pulsating flow conditions;

Δp_{po} is the instantaneous differential pressure across the primary element under undamped pulsating flow conditions where

$$\Delta p_{\text{po}} = \overline{\Delta p}_{\text{po}} + \Delta p'_{\text{po}} \tag{8}$$

NOTE 1 Reliable measurements of $\overline{\Delta p}_{\text{po}}$ and $\Delta p'_{\text{po,RMS}}$ can only be obtained if the recommendations given in 6.1.2 and 6.1.3 are strictly adhered to.

NOTE 2 If it is possible to determine Δp_{ss} Formula (6) is to be preferred. Formula (7) only gives reliable results if $\left(\Delta p'_{\text{po,RMS}}/\overline{\Delta p}_{\text{po}}\right) < 0{,}5$.

5.5.5.2 Turbine flowmeter

The raw signal from a turbine flowmeter is in the form of an approximately sinusoidal voltage with a level which varies with the flow but is usually in the range 10 mV to 1 V peak to peak. In most installations this signal is amplified and converted to a stream of pulses. The extraction of information about the amplitude and waveform of any flow pulsation from the variations in the frequency of this pulse train depends on the value of the dynamic response parameter of the flowmeter. Flowmeter manufacturers do not normally specify the response parameter for their flowmeters, and the measurements which would be necessary to determine it are unlikely to be possible on an existing flowmeter installation. However, the dependency of the parameter on the geometry of the turbine rotor and on the fluid density is discussed in 6.2.1.4, and the range of values which have been found for typical flowmeters is presented in 6.2.1.6, Table 1.

The response of a turbine flowmeter to flow pulsation is discussed in 6.2.1. It can range from the ability to follow the pulsation almost perfectly (medium to large flowmeters in liquid flows) to an almost total inability to follow the pulsation (small to medium flowmeters in gas flows with moderate to high frequencies of pulsation). This latter condition is a worst case for a turbine flowmeter installation because not only does the flowmeter output not show significant pulsation but if the flow pulsation is of significant magnitude, the apparently steady flowmeter output is not a correct representation of the mean flow. If this condition is suspected, other means of measuring the flow pulsation should be employed.

In any particular installation, the first step in an attempt to interpret a turbine flowmeter output should be to take the best available estimate of the flowmeter response parameter and using the results summarized in 6.2.1, to estimate the general nature of the flowmeter response. In the interpretation of any observable fluctuations in the turbine flowmeter output, unevenness in the spacing of the turbine blades can give the appearance of flow pulsation at the rotor frequency. Unevenness in blade spacing might be a result either of damage caused by the passing of a solid through the flowmeter or of manufacturing tolerances. Unevenness of as much as 3 % or 4 % in the blade spacing has been observed in a number of installations. A procedure for processing a turbine flowmeter output signal to remove the effect of uneven blade spacing is given in Annex C.

If preliminary estimates of the frequency of any pulsation in the flowmeter output and the general nature of the flowmeter response combine to suggest that the amplitude of pulsation in the flowmeter output is being attenuated by limited flowmeter response, it might be possible to correct the output. Two possible methods of correction have been described by Cheesewright et al.[7] and by Atkinson[8]; both are summarized in Annex C. Within the constraints of the uncertainty about the value of the flowmeter response parameter, this procedure can yield estimates of the amplitude and waveform of the flow pulsation.

5.5.5.3 Vortex flowmeter

The vortex flowmeter output can be used for instantaneous flow measurements, and hence amplitude and waveform information, in a range restricted to pulsation frequencies less than 2,5 % of the lowest mean-flow vortex-shedding frequency. Limited information can be obtained at higher pulsation frequencies but, in order to avoid the substantial flowmeter errors which can arise from the shedding frequency becoming locked-in to the pulsation frequency (see 6.3.1.3), the pulsation frequency should be less than 25 % of the mean-flow shedding frequency. The detection of pulsation frequencies substantially above the mean-flow shedding frequency can be achieved by spectral analysis. The pulsation frequency is indicated by a local peak in the power spectrum.

6 Measurement of the mean flowrate of a pulsating flow

6.1 Orifice plate, nozzle, and Venturi tube

6.1.1 Description of pulsation effects and parameters

6.1.1.1 Square-root error

For steady flow, the flowrate through a restriction such as an orifice plate is proportional to the square-root of the differential pressure measured between upstream and downstream tappings. The relationship is given by

$$q_m = C_\mathrm{D} \pi \frac{d^2}{4} \varepsilon_\mathrm{ss} \sqrt{\frac{2\rho \Delta p_\mathrm{ss}}{1-\beta^4}} \quad (9)$$

If this relationship was assumed to apply instantaneously during pulsating flow, i.e. assuming quasi-steady conditions, the time-mean flowrate would be inferred from a measurement of the time-mean value of $\Delta p^{1/2}$.

Any attempt to infer the time-mean flowrate from the square-root of the time-mean value of Δp would result in a square-root error, because

$$\left(\overline{\Delta p}\right)^{1/2} \neq \overline{\Delta p^{1/2}} \quad (10)$$

In fact, the quasi-steady assumption is only valid for very low pulsation frequencies in incompressible flow. For a more complete understanding of pulsating flow behaviour of DP flowmeters it is necessary to consider temporal inertia effects, compressibility effects, and factors affecting the discharge coefficient. A brief account of these is given in 6.1.1.2 and 6.1.1.3, and further details can be found in A.4 and in Gajan et al.[9].

6.1.1.2 Temporal inertia

When the flowrate is varying rapidly there is a component of differential pressure required to generate the temporal acceleration in addition to that required for the convective acceleration of the fluid through the restriction. The flowrate-differential pressure relationship is thus

$$\Delta p_{\mathrm{p}} = K_1 \frac{\mathrm{d}q_m}{\mathrm{d}t} + K_2 q_m^2 \tag{11}$$

On the right-hand side of Formula (11), the first term is the temporal inertia term and the second term is the convective inertia term. The temporal inertia term is a function of the non-dimensional frequency known as the Strouhal number, Sr_d, with respect to the throat bore, d, of the orifice, nozzle or Venturi tube, where

$$Sr_d = \frac{f_{\mathrm{p}} d}{\overline{U}_d} \tag{12}$$

In the basic quasi-steady/temporal inertia theory the coefficients K_1 and K_2 are assumed to be constant and are defined as

$$K_1 = \frac{4L_{\mathrm{e}}}{\pi d^2 C_{\mathrm{c}}} \tag{13}$$

$$K_2 = \frac{1 - C_{\mathrm{c}}^2 \beta^4}{C_v^2 C_{\mathrm{c}}^2 (\pi d^2/4)^2} \frac{1}{2\rho} \tag{14}$$

or alternatively

$$K_2 = \frac{1 - \beta^4}{C_{\mathrm{D}}^2 (\pi d^2/4)^2} \frac{1}{2\rho} \tag{15}$$

where

C_{D} is the overall discharge coefficient;

C_{c} is the contraction coefficient;

C_v is a velocity coefficient.

The temporal inertia term is also a function of the geometry of the restriction and the axial distance between the pressure tappings, and thus the coefficient K_1 contains L_{e}, an effective axial length of the primary device.

In pulsating flow the velocity profiles upstream and through the restriction are varying cyclically and, thus, K_1 and K_2 are varying cyclically and even their time-mean values are not necessarily equal to the steady flow values, except when pulsation amplitudes and frequencies are small.

6.1.1.3 Discharge coefficients

In steady flow, the discharge coefficients of all the different types of primary device are dependent on the velocity profile of the approaching flow. The orifice plate tends to be particularly sensitive to variations in velocity profile because of the jet contraction effect. A flatter than normal velocity profile increases the contraction effect and consequently reduces the discharge coefficient. A velocity profile which is more peaked than normal has the opposite effect.

In pulsating flow, the instantaneous velocity profile is varying throughout the pulsation cycle. The degree of variation is dependent on the velocity pulsation amplitude, the waveform and the pulsation Strouhal number. As a consequence, the instantaneous discharge coefficient also depends on the phase