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FROM THE SINGING TELEGRAPH WIRES TO THE TEMPERATURE CONTROL OF WAKES

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Summary: *Vortex shedding from a bluff body is a classical problem as well as an exciting challenge for fluid mechanics. Since the time of Prof. Strouhal at the end of the 19th century, the phenomenon has been frequently studied by several generations of researchers. This contribution introduces (1) the historical context of the milestone studies, (2) motivations and goals of the recent investigations, and (3) recent original results of research on the fluid dynamics and heat transfer of heated and cooled circular cylinders in the cross-flow, obtained mainly in the Institute of Thermomechanics.*

1. Introduction - the historical context

A reference of one of the first observations of wakes is usually dedicated to the most versatile genius of the Renaissance, Leonardo da Vinci (1452–1519). Usually mentioned is his drawing of St. Christopher at the river, where a vortex wake is shown behind his immersed stick (e.g. Zdravkovich, 1997). Understandably, much older historical evidences that the human mind was always fascinated by fluid flows around and behind obstacles can be found – e.g. Nakayama et al., 2002 referred rather seriously that patterns of an ancient Japan pottery (2500 BC) was created according to the von Kármán vortex street. To support this speculation, Nakayama et al., 2002 made an observation of vortices behind a rock of river, laboratory visualization by means of the hydrogen bubbles method in water, and two-dimensional numerical simulation using the finite difference method.

Prof. Čeněk (Vincent) Strouhal (April 10, 1850 in Seč – January 23, 1922 in Prague) experimentally investigated the phenomenon of “singing wires” (or the so-called audible tones, misleadingly called “friction tones” at that time). He was the first who measured the wake frequency and found that the pitch of audible tones depends on velocity and diameter of the cylinders (wires) only – Strouhal, 1878. He explained that the reason of the tones is air flowing around a cylindrical body generating alternating vortices. His original data was published in graphical form of the linear relationship between frequency (f) and velocity (U) with the diameter (D) as parameter, and he generalized the proportionality $f\,D/U = constant$. Much later, this constant was called *„Strouhal number“* by Bénard, 1926. However, Bénard’s suggestion was not accepted outside France until Kovasznay, 1949 and Roshko, 1952 adopted it in their works.

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Since that time, flows around circular cylinders were studied by many investigators – see, e.g., an exhaustive monograph by Zdravkovich, 1997, where nearly one thousand relevant references have been collected. The relationship between the wake frequency and the velocity has been frequently investigated. Nowadays, it is well known that a very advantageous expression of this relationship is the dimensionless relationship between the Strouhal and Reynolds numbers. Probably the first formula was proposed by *Lord Rayleigh* (J.W. Strutt, November 12, 1842 in Essex, England – June 30, 1919 in Essex, England) in 1896 – see Eq. (1) in the text below. However, in the time of Strouhal's discovery (1878), the Reynolds number was unknown yet – it was formed five years later, in 1883, by *Osborne Reynolds* (August 23, 1842 in Belfast, Ireland – February 21, 1912 at Watchet in Somerset, England).

The alternating double row of vortices behind a bluff body in a fluid stream is now named as the von Kármán Vortex Street according to *Theodore von Kármán* (May 11, 1881 in Budapest, Hungary – May 7, 1963, Aachen, Germany). Note that the first clear sketch of an alternating vortex double row was made by Henri Bénard (1874-1939) in 1908 (and errata of this paper were published five years later – Bénard, 1913). Bénard observed and photographed visible dimples on the water surface behind towing circular cylinder. Nevertheless, an explanation of this phenomenon based on analysis of stability was suggested by Kármán, 1911.

The phenomenon of vortex shedding from a bluff body is of fundamental importance in the theoretical study of hydrodynamic instability which includes many problems dealing with the wake flow dynamics (e.g., Monkewitz et al., 1996), such as the onset of vortex shedding, the passing frequency of vortices etc. On the other hand, the phenomenon of vortex shedding is very important from the practical engineering point of view. It influences the drag as well as the heat transfer in external flows. It is considered as one of the sources of the flow-induced vibrations, noise, or even the body collapse. It is worth to mention here the well-known disaster of the *Tacoma Narrows Bridge* in November 7, 1940. The bridge was 1.8 km long and the height of its supporting towers was about 130 m. It was familiarly called "Galloping Gertie", because oscillations of the roadbed occurred even during moderate breezes. People experienced the sensation of crossing the rolling center span, with disappearance and then reappearance of cars in its undulating roadway. Approximately 5 months after its opening, in the morning of 7^{th} November 1940, wind of 60–70 km/h put the bridge into two-dimensional vibrations. Fortunately, the traffic was closed at that moment. After that, the character of the motion dramatically changed from rhythmic rising and falling in a twisting motion of torsional oscillations, which led to the final collapse. One of the first explanations was suggested by T. von Kárman, who was convinced that the reason was the *resonance effect* of the vortex shedding and the natural mechanical vibrations – see Billah and Scanlan, 1991. In fact, the true reason was the more complex phenomenon of the *self-excited vibrations* and *aerodynamic instability*, which developed when alternating forces were created and controlled by the motion itself (Billah and Scanlan, 1991). Therefore, the Tacoma Narrows Bridge disaster was *not* a typical example of forced resonance as had been originally understood and referred to as on certain occasions since that time. Despite that, it remains the most well-known structural failure due to flow-induced vibrations and aero-elasticity interactions. Moreover, this memento stimulated huge progress in mathematical theories of vibration, aerodynamics, wave phenomena as well as in modeling and wind-tunnel testing.

2. Non-isothermal vortex shedding – motivations of the recent investigations

Fluid mechanics point of view

The Reynolds number of flow around a circular cylinder is commonly defined as $Re = U_\infty D/\nu$, where U_∞ is the free-stream velocity, D is the cylinder diameter, and ν is the kinematic viscosity. Since the kinematic viscosity is a function of temperature, the subscript used for the referred temperature can also be attached to Re in general (in non-isothermal flow), e.g., $Re_\infty = U_\infty D/\nu_\infty$, where ν_∞ is the kinematic viscosity based on the free-stream temperature T_∞.

The onset of the vortex shedding for an isothermal cylinder, otherwise, the lower limit of the vortex shedding regime (*critical Reynolds number* Re_C) was studied many times. The commonly cited Re_C value ranges from 40 to 49, e.g., $Re_C = 40$ by Kovasznay, 1949; 44 by Collis and Williams, 1959; 45.9 by Lange et al., 1998; 47 by Fey et al., 1998; 49 by Williamson, 1996.

The thermal effect at forced convection changes the onset of the vortex shedding. For example, the air wake flow is stabilized by the bluff body heating. Cylinder heating suppresses the instability onset in air, thus the Re_C value significantly increases. Explanation for this thermal effect is due to the increase of the air kinematic viscosity with temperature, which causes the decrease of the local Reynolds number (e.g. Lecordier et al., 1991). The other known explanation of the thermal effect in air emphasizes a reduction of fluid density by increase of temperature thus a reduction of absolute instability (Yu, Monkewitz, 1990). The other possible approach can be based on the analytical attitude to the variable properties of fluids (e.g., Herwig and Wickern, 1986).

The kinematic viscosity used in the Reynolds number is commonly connected with the upstream flow property in the case of isothermal flow, since the values of fluid properties in the whole flow field are the same. However, there is an appreciable variation between the cylinder wall and free-stream conditions for the heated cylinder case (e.g. hot wire). An artificial temperature, the so-called "film" temperature T_f, was customarily introduced for the heated case and the flow properties were based on this film temperature. The film temperature is defined as the arithmetic mean of the cylinder wall T_W and the free-stream temperature T_∞ as $T_f = (T_W + T_\infty)/2$.

However, the physical significance for T_f has not been discussed in the literature. To bring more physics to the Reynolds number, Lange et al., 1998 has taken the fluid properties directly based on the cylinder wall temperature, however, the result was temperature-dependent even for moderate temperature ratio $T^* = T_W/T_\infty \leq 1.5$ (both temperatures are in Kelvin).

If the idea of the so called *effective temperature* is applied, the onset of vortex shedding even for a non-isothermal cylinder can be described by the definite Reynolds number value, *critical effective Reynolds number* $Re_{C,eff}$, which is the same for both non-isothermal and isothermal cylinders. The idea of the effective temperature (*"T_{eff}-concept"* or *"Re_{eff}-concept"* in short) was proposed originally by Lecordier et al., 1991, and used later by Dumouchel et al., 1998, Lecordier et al., 2000. They calculated the effective kinematic viscosity ν_{eff} from an effective temperature T_{eff} that is defined by $T_{eff} = T_\infty + C\,(T_W - T_\infty)$, where the constant C was originally suggested $C = 0.3 \pm 0.025$ by Lecordier et al., 1991, and later reported C = 0.24.

Dynamics of the wake behind a bluff-body is quantified by means of the Strouhal number, $St = f\,D/U_\infty$. For the *St-Re relationship* of the isothermal flow, several equations of *St-Re*-curve have been proposed in the literature. Probably first formula was proposed by Rayleigh, 1896 in the following form

$$St = 0.195\left(1-\frac{20.1}{\mathrm{Re}}\right) \quad (1)$$

This equation agrees quite well with pioneer experiments by Strouhal, 1878 – it is shown in the monograph by Zdravkovich, 1997. Roshko, 1952 summarized his own hot-wire measurements in the approximation of the *St-Re*-curve as

$$St = 0.212\left(1-\frac{21.2}{\mathrm{Re}}\right). \quad (2)$$

Following this equation, Williamson, 1988 proposed the form as

$$St = \frac{A}{\mathrm{Re}} + B + C\,\mathrm{Re}, \quad (3)$$

where $A = -3.3265$, $B = 0.1816$ and $C = 1.6 \times 10^{-4}$. This formula has shown as a good representation for unheated cylinder and deviations of this formula from Eq. (2) by Roshko, 1952 are within –1.3% to 2.0%. More recently, Williamson and Brown, 1998 have proposed an expansion of power series of $(1/Re)^{0.5}$ for a wide range of Re from 50 up to 1.4×10^5 as:

$$St = D + \frac{E}{\sqrt{\mathrm{Re}}} + \frac{F}{\mathrm{Re}} + \dots \quad (4)$$

For laminar parallel shedding in the range $49 < Re < 180$, the constants *D, E* and *F*, respectively, are given as 0.2850, –1.3897 and 1.8061 for the 3-term truncated series and 0.2665, –1.0175 and 0 for the 2-term truncated series. Independently, Fey et al., 1998 gave a two-term series representation with constants D=0.2684, E = –1.0356, and F = 0. The *St* values calculated from above-proposed Eqs. (3 and 4) agree quite well with each other and the maximum difference between them is less than 1% in the range of $50 \le Re < 180$.

All these *St-Re* equations (1–4) are valid for the isothermal cases only. Surprisingly, the influence of heating on the frequency of vortex shedding had not been known until 1999. At that time, no *St-Re* relationship was known for the flow around non-isothermal cylinders (!) Beside that essential contradictions in the understanding of the temperature influence on the frequency of vortex shedding existed:

- Lange et al., 1998 made two-dimensional numerical investigations in the moderate range of "temperature loading" T^* = 1.003 to 1.5. They concluded that *the vortex shedding frequency is almost unaffected by the surface temperature.*
- Quite opposite results were reported by Yahagi, 1998, who conducted experiments at $Re = 260$ and with very wide temperature range for T^*-value up to about 3.0. He concluded that the *vortex shedding frequency decreased with increasing cylinder temperature.* The frequency decrease was 4.2%, 8.8% and 13.5% at T^* = 1.61, 2.30 and 2.98, respectively.

It is worthy noting here that a precise experimental evaluation of the "universal" *St-Re* curve is intrinsically complicated. It has been found that there exist *discontinuities in the St-Re curve* if the wake is under the influence of the so-called end effects caused by the end conditions of the tested cylinders (Williamson, 1988 and 1996). Under these circumstances, the vortex shedding from a cylinder does not become parallel, instead, it becomes slanted to the cylinder axis despite the setup of the tested cylinder in the cross-flow can be "perfect". Different *end-manipulating methods* to isolate the end effects, and generate the parallel vortex shedding, have been proved. This flow control can be both active and passive; the former, as, e.g., the end-suction method, was developed by Miller and Williamson, 1994, the latter include methods of the end-cylinders (Eisenlohr and Eckelmann, 1989), inclined end-plates (Williamson, 1989), and transverse control cylinders (Hammache and Gharib, 1991).

However, all the above end-manipulating methods concern isothermal flows, and none of them is applicable to heated or cooled cylinders. It is important to ensure accurate evaluation of the *St-Re* relationship, one has to carry out the experiments in the parallel vortex shedding mode (i.e. two-dimensional wake flow). If vortex shedding is slanted, the frequency is influenced by the additional parameter – the angle of vortices, which complicates the evaluation of experimental data.

Heat transfer point of view

One of the older relations focused on the forced convective heat transfer from a circular cylinder in cross-flow is the theoretically proposed King's law (from 1914; cited e.g. by Hinze, 1975, p.88). Its main result is a square-root dependence of the Nusselt number on the Reynolds number. The Nusselt number *Nu* is defined as $Nu = h\ d\ /\ k$, where h is the mean heat transfer coefficient over the whole cylinder surface and k is the thermal conductivity of the fluid. A typical heat transfer relationship can be expressed for a moderate temperature loading in the form

$$Nu = (A\ Pr^{p} + B\ Pr^{q}\ Re^{n}), \tag{5}$$

where A, B, n, p, q are experimentally determined constants, and Pr, is the Prandtl number. Evidently, heat transfer varies predominantly with Reynolds and Prandtl numbers and many other parameters affect the process such as temperature loading, boundary conditions, aspect ratio (end effects), blockage effects due to the wind tunnel and wakes, and free-stream turbulence.

Some efforts have been made to implicitly express the effect of temperature loading (or temperature ratio T^*) in the heat transfer relation by using different reference temperatures. Fluid properties are usually based on the film temperature T_f. However, none of those efforts are able to really account for the influence of temperature loading except for moderate T^*-range where the effect is insignificant (say $T^* < 1.5$). The commonly used heat transfer relationships for larger T^*-values ($T^* > 1.5$) are in the form

$$Nu_f = (A\ Pr^{p} + B\ Pr^{q}\ Re_f^{\ n})\ F^{r}, \tag{6}$$

where $Nu_f = h\ d/\ k_f$ and $Re_f = U_\infty\, d\ /\nu_f$. The temperature loading factor F^r is based either on the ratio of $T_f\ /T_\infty$ (e.g. Hatton et al., 1970, Collis and Williams, 1959, Fand and Keswani, 1972, and recently Lange et al., 1998) or T^*, or the ratio of T_W/T_∞ (e.g. Morgan, 1975 and Hilpert, 1933). The empirical constant r has mostly taken as 0.17 for the former case (except $q = 0.154$ was used in Hatton et al., 1970), and $r = n/4$ for the latter cases.

A large number of investigators have evaluated the constants of equation (6). The representative collection can be found in the excellent review of Morgan, 1975 or other publications – e.g. Zukauskas and Ziugdza, 1985, Lange et al., 1998, and Churchill and Bernstein, 1977. The values of empirical constants A, B and n were suggested by Hilpert, 1933 and Morgan, 1975 as $A = 0$, $B = 0.795$, $n = 0.384$ for the laminar steady recirculation regime, and $A = 0$, $B = 0.583$, $n = 0.471$ for laminar vortex shedding regime, respectively. The border of both regimes was at $Re_f = 35$.

The *temperature loading factor* F^r is a generally accepted non-negligible term in the heat transfer description. It can be omitted only at low temperature differences. Elimination of the temperature loading factor at higher temperature differences is desirable from both theoretical as well as practical point of view. Obviously, the influence of temperature can be partly included in the heat transfer description by a definition of fluid properties, often accepted is the definition at the "film temperature" (Eckert and Drake, 1972). Moreover, many other evaluations are possible including analytical approach (Herwig and Wickern, 1986).

However, any of the known classic evaluations does not eliminate entirely the influence of the temperature loading, but only at a moderate range.

However, as discussed above, the critical Reynolds number Re_C (i.e., the border of both regimes) is a function of temperature ratio. This is also one reason to encourage by using the effective Reynolds number for describing the heat transfer correlation equation from this aspect. Moreover, since in most tests the wake from the heated cylinder might not be truly two-dimensional, it is important to examine the influence of the three-dimensional vortex shedding pattern on the heat transfer of the heated cylinder. Therefore, another motivation of the recent investigations is to investigate the effect of three-dimensional wake pattern on heat transfer. The following text discusses four problems which have been successfully studied with participation of the Institute of Thermodynamics.

3. Temperature control of vortex shedding - selected results from the last five years

(a) *Thermal effects and the critical Reynolds number*

It has been experimentally proved that the air wake flow is stabilized by the bluff body heating: Cylinder heating stabilizes the air wake flow, and the heating can even suppress the onset of the laminar vortex shedding (Wang, Trávníček, and Chia, 2000). Fig. 1 shows this stabilization effect – the critical Reynolds number Re_C increases with increasing temperature T_W. Clearly, the cylinder cooling destabilizes the air wake flow and the onset of the laminar vortex shedding can be even initiated by cooling (Trávníček, Wang, and Maršík, 2002).

Based on the T_{eff}-concept, the T_{eff} was derived by Wang, Trávníček, and Chia, 2000 from experiments as

$$T_{eff} = T_\infty + 0.28\,(T_W - T_\infty). \qquad (7)$$

The T_{eff} is not "only an artificial value" like the well known film temperature T_f. The effective temperature is close to the hot recirculation zone temperature (Dumouchel et al.,1998). Moreover, the maximum temperature in the wake measured by Yahagi, 1998 is apparently very close to the calculated T_{eff} – according to the evaluation by Wang, Trávníček and Chia, 2000.

The onset of the vortex shedding for a heated cylinder is characterized by the *critical effective Reynolds number* $Re_{C,eff} = 47.5 \pm 0.7$ (Wang, Trávníček and Chia, 2000). Fig. 1 demonstrates this result: by using the Re_{eff}–concept when T_{eff} is computed from Eq. (7), all experimental data (hot-wire measurement as well as smoke wire visualization) collapse on the constant value $Re_{C,eff} = 47.5 \pm 0.7$.

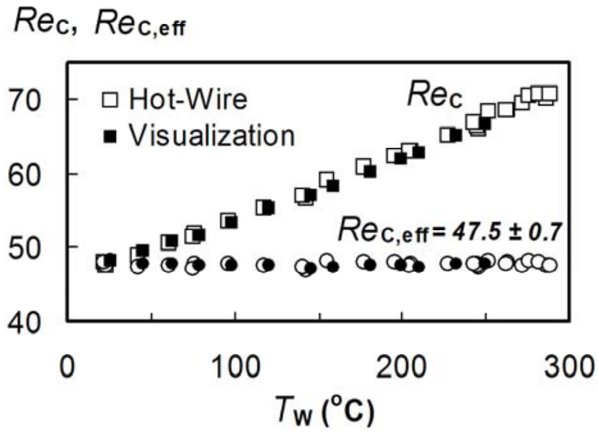

Fig. 1. Wake flow in the critical stage – the Re_C increases with increasing T_W. Open symbols represent the hot–wire measurement, solid symbols represent the smoke-wire visualization.

(b) *End-manipulating method for non-isothermal parallel vortex shedding*

The "transverse control cylinders technique" originally developed by Hammache and Gharib, 1991 has been chosen as the basic. That technique works satisfactorily for the isothermal case only.

The new method uses a pair of additional fins on the cylinder ends, which are used as the heat sink to reduce the temperature within the wake after the transverse control cylinders. The air viscosity is decreased and the local Reynolds number is increased there, and the parallel vortex shedding is effectively stabilized (Wang, Trávníček and Chia, 2000).

(c) *Universal* St-Re_{eff} *relationship*

It has been proved and quantified, that the frequency of vortex shedding (or *St*-value) decreases for the increasing cylinder temperature (Wang, Trávníček, Chia, 2000). It was revealed that the frequency data of the heated and unheated circular cylinders successfully collapsed to the "universal" St-Re_{eff}-curve for different temperature ratios by using the Re_{eff}–concept, when T_{eff} is computed from Eq. (7). The St-Re_{eff}-curve is written as:

$$St = 0.2660 - \frac{1.0160}{\sqrt{Re_{\mathrm{eff}}}} . \qquad (8)$$

A comparison of equations (8) and (4) can be performed in the isothermal case, where the $Re = Re_{\mathrm{eff}}$. The maximum deviation of equations (8) and (4) has been less than 0.23 % in the laminar vortex shedding regime for $Re \leq 180$, see Wang, Trávníček, Chia, 2000.

Fig. 2 and 3 show the *St-Re* and St-Re_{eff} relationships for isothermal and both non-isothermal cases of the heated/cooled cylinders. Fig. 2 demonstrates the thermal effect: cylinder heating stabilizes wake flow (thus frequency decreases) and cylinder cooling destabilizes. It gives an illustrative graph of a family of the *St-Re*–curves with temperature as a parameter.

The „universal" St-Re_{eff}-curve for isothermal and both non-isothermal cases of the heated/cooled cylinders is plotted in Fig. 3. All frequency data of the heated and unheated cylinders collapse to the "universal" St-Re_{eff}-curve of Eq. (8).

Fig. 4 has been reproduced from the paper by Shi et al., 2004. It contains the comparison of the *St-Re*

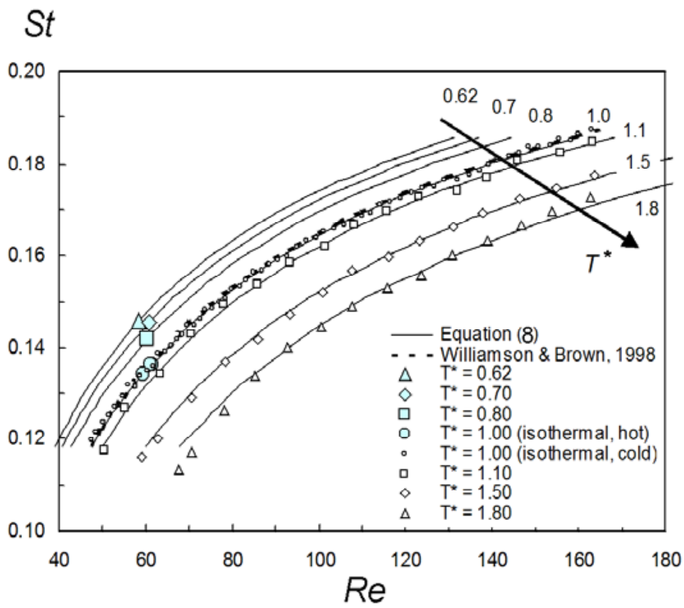

Fig. 2. The *St-Re* relationship for isothermal (T^*=1.00) and both non-isothermal cases of the cooled (T^*<1.00) and heated (T^*>1.00) cylinders.

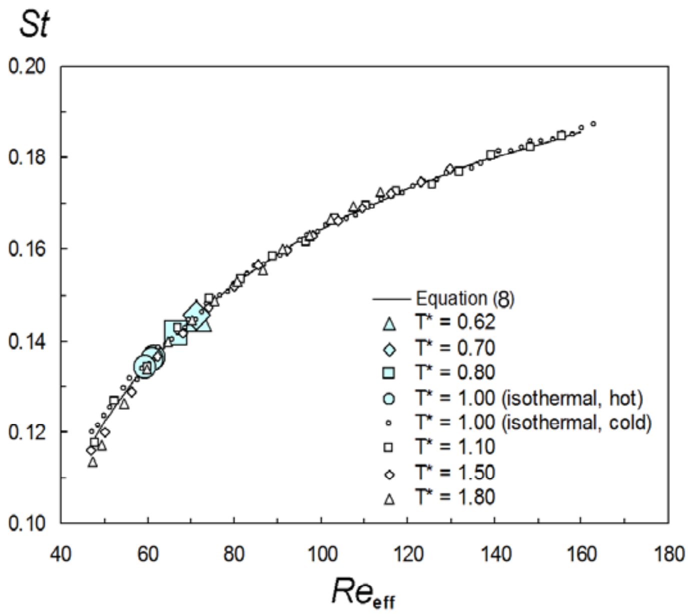

Fig. 3. The "universal" St-Re_{eff} relationship.

relationship for isothermal and moderately heated (T^* = 1.5) cylinders. Most results shown in Fig. 4 are the numerical results which have been obtained by the team of Prof. F. Durst (Universität Erlangen-Nürnberg, Germany). The reference experimental data for the isothermal cylinder are represented by Eq. (4) (Williamson and Brown, 1998). The reference data for the heated cylinders are represented by the results of Wang, Trávníček and Chia, 2000. The author highly appreciates that the results published in Wang, Trávníček and Chia, 2000 were used as the reference data in the *Physics of Fluids* paper by Shi et al., 2004.

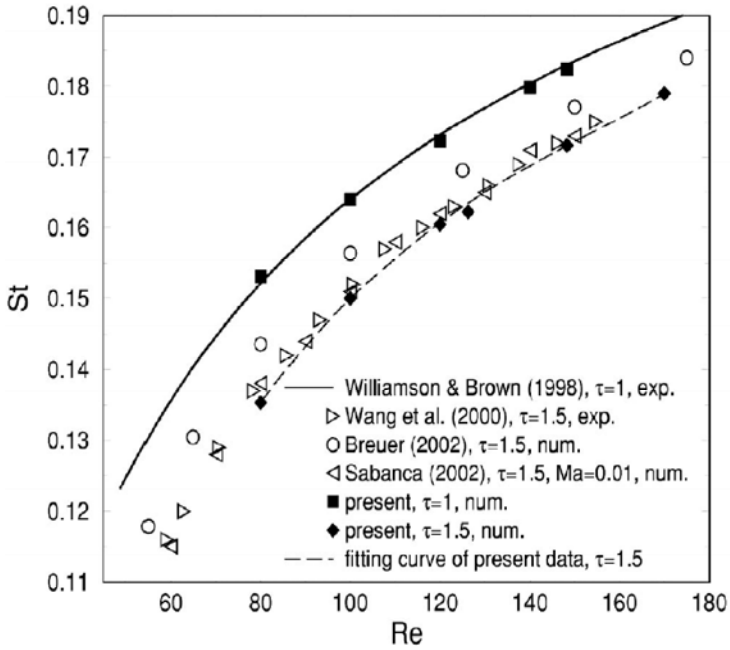

Fig. 4. Influence of the overheat ratio on the Strouhal number versus the ambient Reynolds number Re; $\tau = T^* = T_W/T_\infty$ (reproduced from Shi, Gerlach, Breuer, Biswas, Durst, 2004).

(d) Elimination of the temperature loading factor from the heat transfer description

New attempt to introduce a representative Reynolds number concept has been suggested by Wang and Trávníček, 2001. The newly proposed "representative Reynolds number" is derived on the basis of an approximation equation of "representative temperature T_{rep}", which is defined as $T_{rep} = T_\infty + 0.36\,(T_W - T_\infty)$. It has been confirmed that a heat transfer correlation can be transformed to an explicit form without the temperature loading factor (or temperature ratio T^*), and it can be independent on the 2D or 3D vortex shedding patterns. A linear form for the Nu_f-$Re_{rep}^{0.5}$ relationship has been proposed as

$$Nu_f = 0.502 + 0.434\, Re_{rep}^{0.5} \quad \text{and} \quad Nu_f = -0.153 + 0.527\, Re_{rep}^{0.5} \qquad (9 \text{ and } 10)$$

for the laminar steady recirculation regime and the laminar vortex shedding regime, respectively (Wang and Trávníček, 2001). Fig. 5 demonstrates the excellent collapse of all experimental data on the linear correlation curve of Eqs. (9 and 10).

It should be emphasized that this approach is focused on the heat transfer at higher temperature differences ($T^* \leq 1.8$), therefore it is based on an adequate treatment of the temperature loading effect. To the contrary, a majority of the known classic heat transfer correlation concerns moderate temperature differences (say $T^* \leq 1.5$), where the temperature loading factor can be easily omitted.

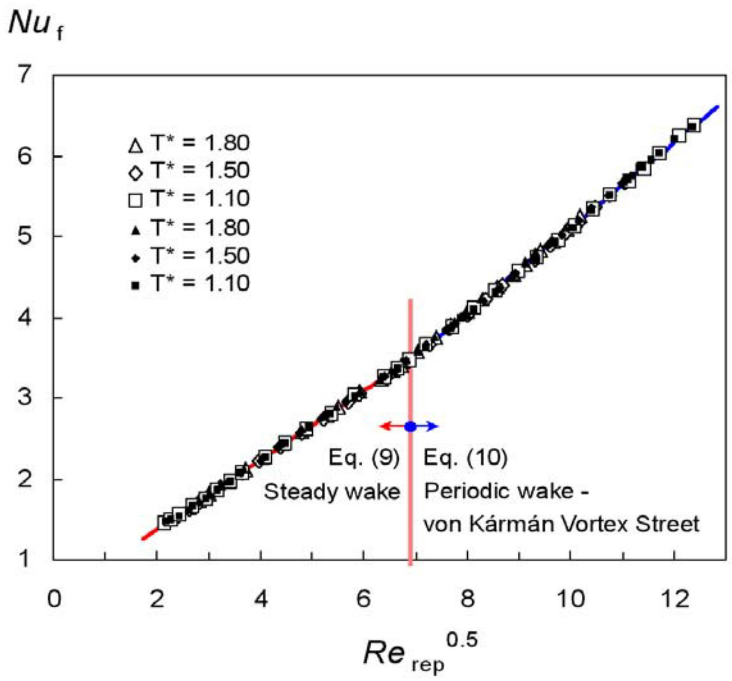

Fig. 5. Linear relationship of Nu_f and $Re_{rep}^{0.5}$ for the steady recirculation and periodic flow regimes.

4. Conclusions

The paper introduces (1) the historical context, (2) motivations and goals of the recent investigations, and (3) recent results focusing on heated and cooled circular cylinders in the cross-flow. The following four original results of the author obtained in the past five years are summarized: (a) the thermal effects, (b) end-manipulating method for non-isothermal parallel vortex shedding, (c) universal St-Re_{eff} relationship, and (d) elimination of the temperature loading factor from the heat transfer description.

The phenomenon of vortex shedding from a bluff body is of fundamental importance to the theoretical studies as well as for the practical engineering applications. Fluid flow around a bluff body is often similar to many real flows, e.g., in very small heat exchangers, typically used for cooling of electronic components. Wake vortices behind bluff bodies are among the main sources of flow-induced vibrations and aerodynamically generated noise, and may result in the body collapse (damage). Thermal effects (heating/cooling) enable control of the boundary layer, flow separation, and drag coefficient. These effects can be important in external and internal aerodynamics (aviation, aeronautics, aircraft propulsion, heat exchangers, turbomachinery, power engineering, etc.).

Wake flow behind heated or cooled circular cylinders is of fundamental importance both for fluid dynamics and heat transfer. It has been target of many investigations in the past, however, the majority of all works have been oriented only to one of these aspects – *either* fluid dynamics *or* heat transfer. It has been shown in this paper that it is necessary to pay equal attention to both aspects, and to their *collective* effect.

5. Acknowledgement

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