Three dimension structured surfaces – Type 1

Structures with one oscillation wave

Contents

1_Introduction

Whilst the benefit of structured surfaces has been known for long, it has mostly been addressed till now to two dimension structures with flow drag reduction limited to 10-12% (see site web section_ Structured Surface 2D). The objective of the present study is to analyse the benefits of more complex structure shapes. Performance of structured surfaces may be analysed in using Computational Fluid Dynamic codes (previous section) ranging from the Direct Numerical simulation (DNS - Full turbulence simulation) to the Reynolds Average Navier Stokes (RANS - Full turbulence modelling). These codes are used for very different purposes. Concerning the first code, it is used for an in depth flow mechanism analysis at the expense of a high computation cost and, concerning the second code, it is used for engineering studies. The Large Eddy Simulation code (LES - Partial simulation and partial modelling of turbulence), intermediate in its features between the two codes, tends to be used more often for engineering applications. It seems to be a good compromise for the study of complex boundary flows.

A RANS code has been successfully used for the study of two dimension (2D) structures providing some means for analysing 2D structures in terms of flow drag reduction and secondary flows around these structures. However, when tested in a more complex boundary flow situation (typically, the case of an oscillating plate), the RANS code failed. As a consequence, LES has been tested for the steady of more complex boundary layers (oscillating plates and 3D structures).

A LES code has been successfully validated in the case of an oscillating plate (Section 2 below). This task was required prior to the study of complex structured shapes.

A LES code has then been used for the study of a specific three dimension (3D) structure (Section 3 below). This 3D structure combines the principle of two turbulence reduction mechanisms: a) 2D structure and b) transverse flow oscillation. These structures appear as sine waves mounted in direction of the main flow with hills and valleys sized similarly to 2D riblets. The amplitude and the period of the sine waves are sized similarly to a transverse oscillating flow (oscillating plate). A parametric study has been carried out in order to verify the effect of a change in both oscillation amplitude and period.

Similitude laws are provided in this report for transposing the results from the present study (Re Nb=14 000) to considerably larger Reynolds numbers (gas transport – $10^7<Re<10^8$). In particular, the 2D structures and sine wave parameters are roughly proportional to the pipe diameter / Reynolds nb ratio (D / Re).

2_Flow simulations of an oscillating wall with a LES code

Fluid flow displacement over 2D structures was satisfactorily simulated with a RANS code. 3D structures present considerably more complex flow dynamics at the wall boundary layer which may be not easily represented by a RANS code. To verify the capability of a RANS code in this respect, flow simulations were first carried out in the case of an oscillating plate moving transversally to the main flow. This arrangement is widely known by the scientific community to provide a drag reduction of the order of 40% (at optimum conditions – No consideration for input energy) since it was discovered in the 90's. Simulations of this phenomenon failed with a RANS code whatever the turbulence model was. Simulations were then carried out with a LES code. Results are presented in this section. It is expected that if a LES code provides satisfactory results in this complex three dimension boundary layer, the code should be found suitable for testing complex wall structure shapes with similar wall flow displacement.

2.1_State of the art

In turbulent boundary layers, channel and pipe flows, a persistent skin friction reduction can be achieved by means of span wise oscillations, as first shown by W.J. Jung et al. (1992). These turbulent flows are of great theoretical and practical interest as they arise in several applied problems: around oscillating bodies, in boundary layers with fluctuating free stream currents and in three dimensional boundary layers.

They were indications in the 80's that when a sudden transverse perturbation is initiated, production of turbulence is temporarily reduced.

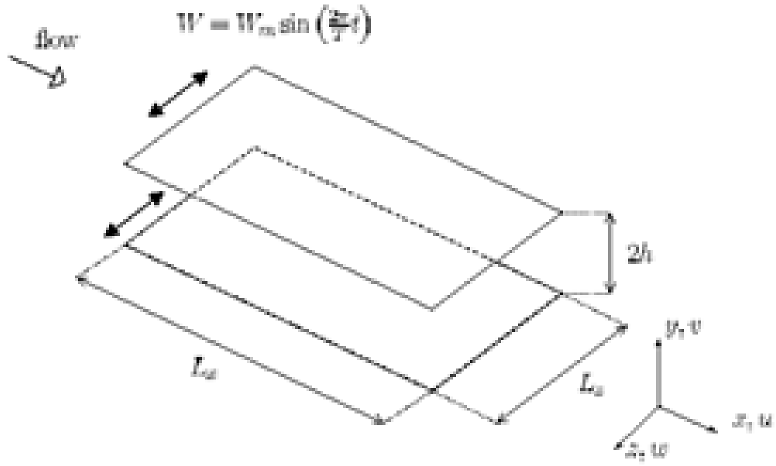

Figure 2.1.1 – Schematic of the spanwise motion of a flat plate (From M. Quadrio – 2003)

W.J. Jung et al. explored the possibility of sustained control of turbulence in wall bounded flows by span wise oscillations by using direct numerical simulation in a rectangular channel. Span wise cross flow and span wise motion were both studied with dimensionless period T+ ranging from 25 to 500. T+ is defined as $T_{osc} / \left(\upsilon / u_\tau^2\right)$ where the three parameters are respectively, the oscillating period, the viscosity and the friction velocity. They show a persistent maximum drag reduction of 40% after the 4th period when T+=100. Away from this value, the drag reduction is smaller.

F. Laadhari et al. (1994) have provided experimental evidence that the turbulence reduction is sustained by using a 1m by 0.7m flat plate oscillating up to 7Hz in a wind tunnel.

To verify if the same drag reduction could be achieved in a circular pipe, K.S. Choi et al. (1997) carried out experiments with water and a 6 m long, 0.0288 m diameter pipe. Oscillations could be handled up to 50Hz at a fixed angle of 30°. 25% drag reduction was achieved but the maximum drag was not reached due to limitation in oscillation frequency and amplitude during experiments.

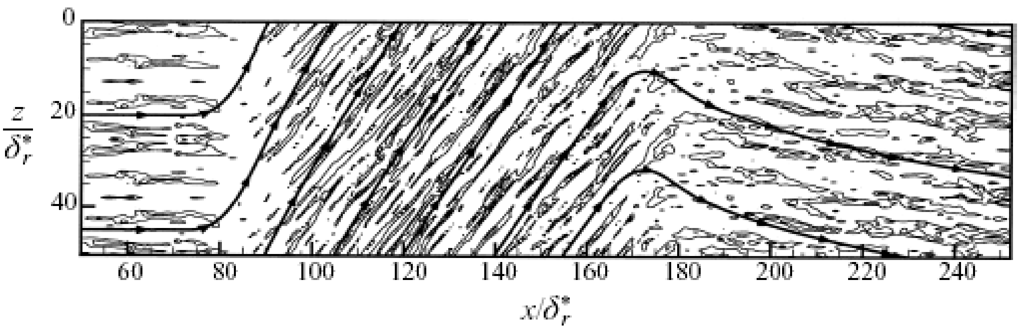

Figure 2.1.2-Contours of negative streamline velocity fluctuations (from C. Kannepalli–2000)

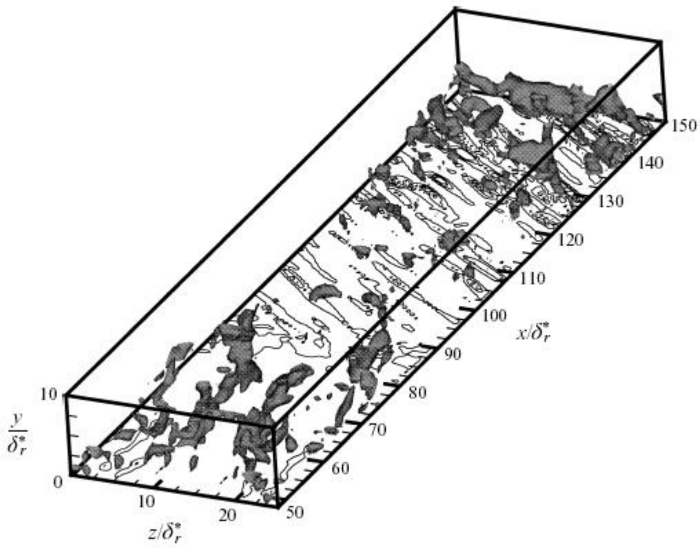

Figure 2.1.3 - Low pressure of iso surfaces superimposed on contours of wall enstrophy (from C. Kannepalli - 2000)

S.M. Trujillo et al. (1997) conducted experiments in a rectangular channel with water. They achieved 25% drag reduction. A greater drag reduction could not be established due to experiment limitations.

J.H. Choi (2002) performed DNS studies on both channel and pipe flows finding the same drag reduction in both conditions. A maximum drag reduction was achieved at T+=100. They studied the dependency of the drag variation with the dimensionless wall velocity (wall velocity divided by friction length) and other parameters.

More recently, Quadrio and Ricco (2003) devoted their attention to the initial transient period which immediately follows the start-up of the oscillations.

2.2_Flow simulations – 1st LES code validation

It is not the intention to report here all the details of the analysis. Only the main elements will be recalled.

The flow simulations were performed in both open and closed rectangular channels.

Two subgrid-scale models are available in the code used: the Smagorinsky-Lilly model and the RNG model based on the renormalization group theory. The last one has been retained because its field of use covers both low and high Reynolds situations and because it is intended to study a turbulent boundary-layer development where Reynolds numbers are varying from near zero, close to the wall, to very large values in the core flow.

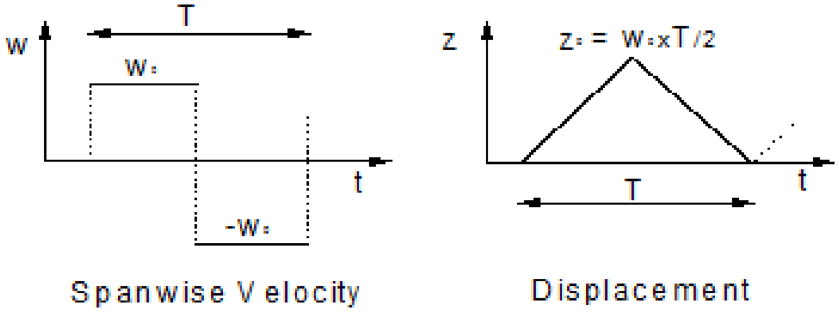

Figure 2.2.1 – Transversal velocity (z direction) and displacement of mowing wall

Flow parameters are non-dimensionalized with respect to wall units. The friction velocity u_τ is defined as: $u_\tau = \sqrt{\frac{\tau_p}{\rho}}$ where τ_p is the shear stress at the wall and ρ the fluid density. The dimensionless time unit, t^+ is defined by: $t^+ = t\frac{u_\tau{}^2}{\nu}$

where t is the physical time and ν is the fluid kinematic viscosity.

Dimensionless coordinates are defined by: $y^+ = y\frac{u_\tau}{\nu}$

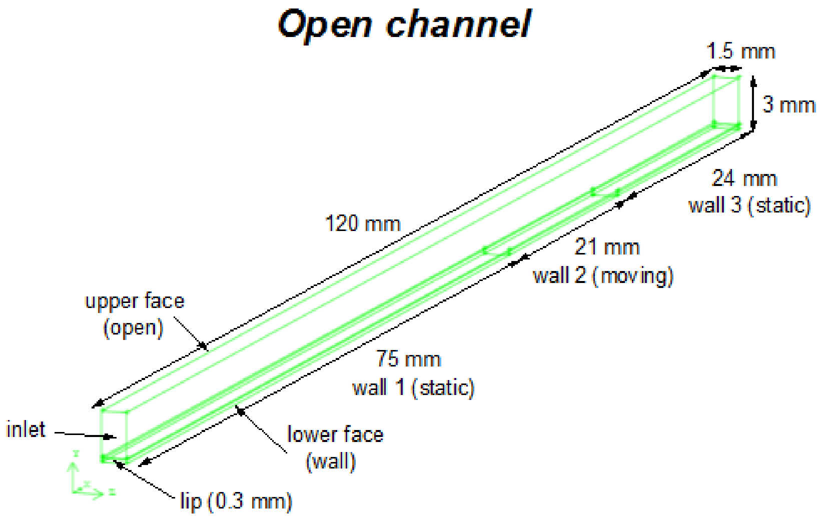

Figure 2.2.2 – Test volume with walls 1 and 3, fixed sections at inlet and outlet and wall 2, located between walls 1 and 3, moving transversally. X, Y and Z are, respectively, for longitudinal, radial (normal to walls 1 to 3) and transversal directions.

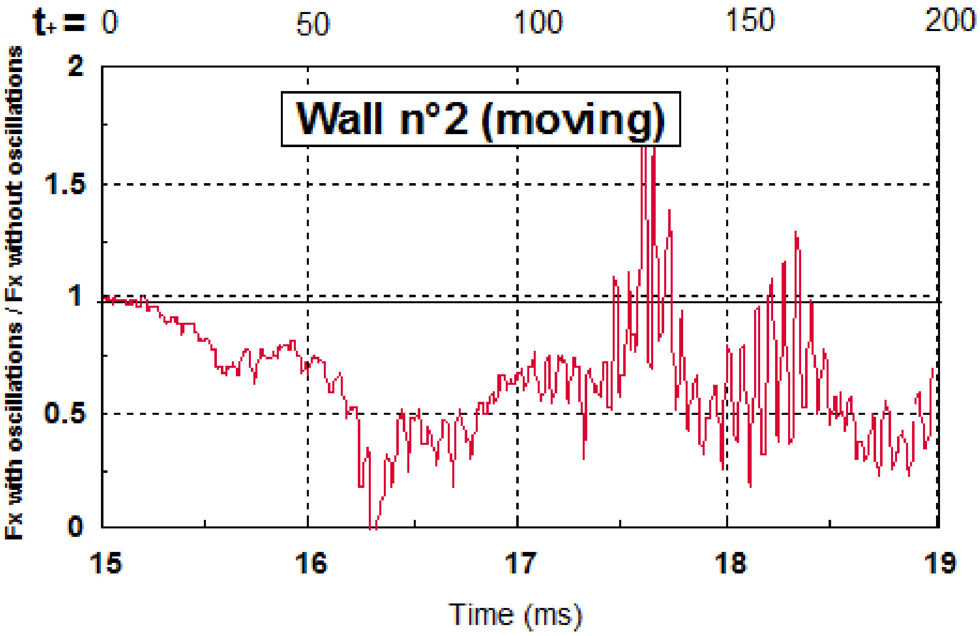

Figure 2.2.3 – Ratio of longitudinal forces along longitudinal direction between two cases: with oscillations and without oscillations.

LES is initiated by a RANS calculation. After LES is started, a certain time (6 ms here) is required for the flow pattern to establish and the turbulence be sufficiently developed. Once turbulence is fully developed, the calculation is prolonged in order to be certain that the flow reaches a steady state. A way to observe flow behaviour and turbulence evolution is to monitor the wall stresses on bottom faces. In the present case, stabilization duration has been estimated to 15 ms (figure 2.2.3) which is a time corresponding to 5 volume sweeps considering an average flow velocity of 40 m/s.

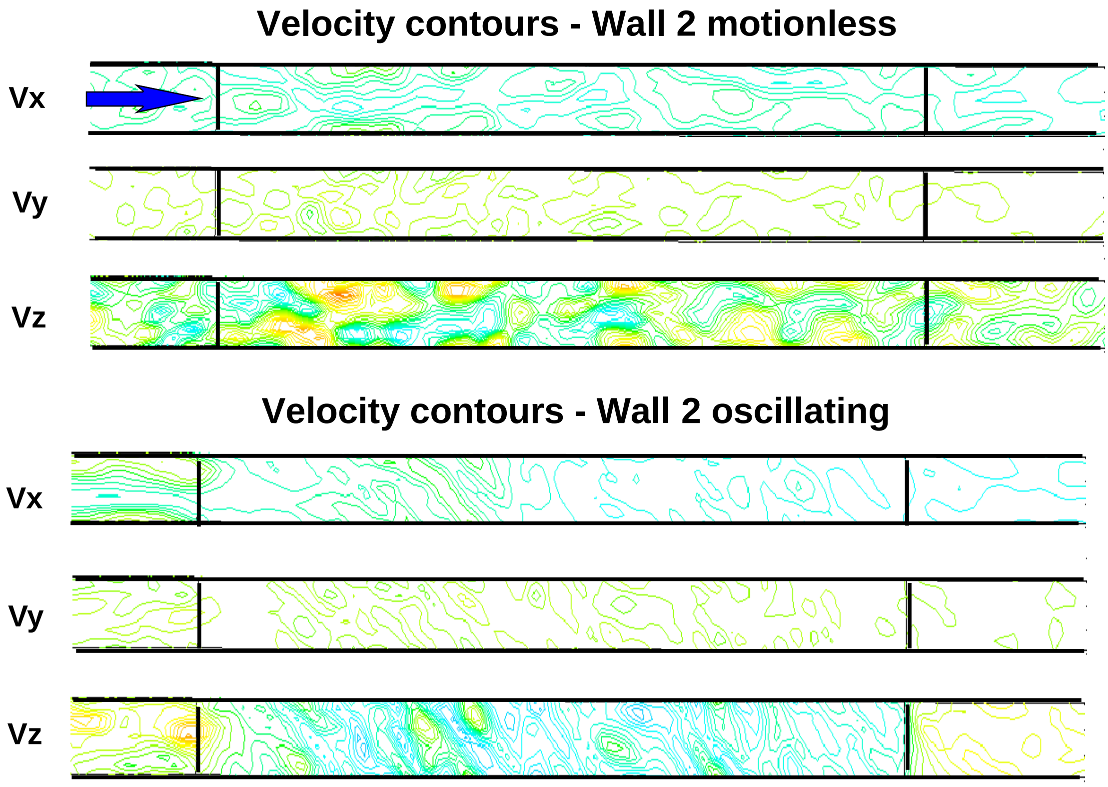

Figure 2.2.4 – Velocity contours for Vx, Vy and Vz in two cases: without and with oscillations

The two significant parameters relative to velocity oscillations are their frequency and their amplitude. Expressed in its scaled form, the period $T^+ = 100$ achieves the highest friction reduction (42%). Two other period values have been tested with $T^+ = 200$ (250 Hz) and $T^+ = 50$ (1000 Hz) providing less friction reduction. The following table presents the results of the analysis.

T^+	Friction reduction
50	37 %
100	42 %
200	32 %

These results are in good agreement with data found in references indicating generally an optimal period nearly 100. The rate of 42 % fits also with what is stated in similar flowing conditions.

The oscillation velocity was tested for three values expressed in its scaled form, W^+ = 12, 24 and 36 with the period T^+ equal to 100. Reduction rates are presented in the next table.

W^+	Friction reduction
12	42 %
24	61 %
36	72 %

It is apparent that the friction reduction rate steadily increases with the oscillation amplitude. This fact is already mentioned in previous works dealing with shear flows. It may not always be seen when friction forces are not recorded during a time sufficiently long because the time needed to the shear friction to reach its lowest stage is gradually increasing with oscillation amplitude. This is probably why some authors did not refer to this point. Calculations were not performed above a value of 36 (W^+)

It has to be pointed out that the friction reduction observed in the longitudinal direction (X) is not related in any way to the energy input in the transversal direction (Y). This consideration would have provided other types of results. It is suggested that some development be carried out in this direction.

CONCLUSION: These flow simulations have shown **the ability of a LES code to represent the flow behaviour and to predict the associated drag reduction provided by the span wise oscillating motion of a plate**. For open and closed channels max flow drag reduction was achieved at a dimensionless period T+ of the order of 100.

On this basis, this LES code is found suitable for analysing the drag reduction provided by most types of three dimension structures.

3_Optimisation of structured surfaces with a LES Code

The performance of several two dimension structures (riblets) was analysed in the previous site web page (Two dimension structures) using a RANS code. This type of code based on turbulent models can provide the effect of the turbulence (energy dissipation) and can be found satisfactory in most engineering applications particularly where energy dissipation follows similitude laws provided by these models. The flow behaviour near a wall with a complex boundary layer requires total or partial simulation of the turbulence near that wall. This is the purpose of this section providing the results of flow simulations with a CFD code based on the simulation of large turbulence eddies (Large Eddy Simulation code).

The work has started with the simulation of two dimension riblets to verify the suitability of a LES code in the simplest case. As the performance of these structures is widely known, it provides a second validation case for this LES code, following the validation made in the case of an oscillating plate.

The work is then continued with a specific three dimension structured surface.

3.1_Two dimension knife blade riblet – 2nd LES code validation

3.1.1_Generalities

There are two main constraints in using a LES code, particularly, with structured surfaces, compared to a RANS code: the computation time and the space definition.

With a RANS code, the flow behaviour is calculated at any time (case of a stationary main flow) representing the average flow situation while with a LES code, the flow evolution versus the time needs to be established, the average flow being subsequently calculated from the time evolution. This is the first reason why it involves a longer calculation time.

With a RANS code, channel periodicities (longitudinal and transverse) may be carried out over short distances (allowing the modelling of a single riblet in the case of a two dimension structure), while an analysis, with a LES code, of the turbulence effects requires a space definition considerably greater for letting the turbulence to evolve. This is the second reason why it involves a longer calculation time.

As a consequence, the analysis bas been simplified in using the most simple two dimension structure: the knife blade riblet requiring rectangular meshing (figure 3.1.1). General observations made on this type of riblet may be transposed to most two dimension riblets (see web page on Two dimension Structure Surfaces – study of riblets with different shapes).

Another way for optimizing the computation time is a proper selection of the Reynolds number defining the channel characteristics and the flow conditions. This number must not be selected too low (too close to the turbulence lower limit - 4000) to avoid damping of the turbulence during calculation and, subsequently, disappearance. This number must not be neither selected too high as the number of meshes is more or less proportional to the square of the Reynolds number with corresponding impact on the computation time. For these reasons, a Reynolds number of 14 000 was selected for the present application.

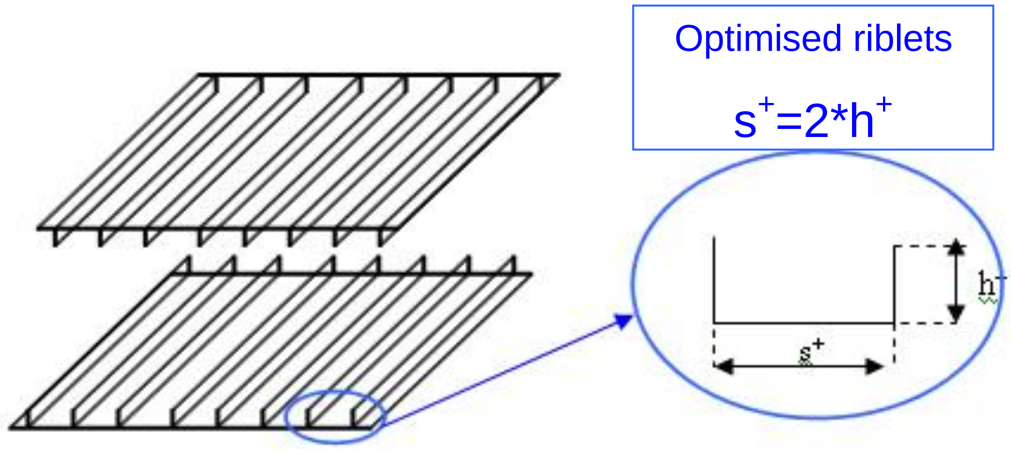

Figure 3.1.1 – Two dimension knife blade riblets with optimum dimensions (riblet height (h) = half riblet width (s)) – Perspective view

The selected flow conditions are the following:

- Density : 1.6 kg/m^3 (ρ)
- Absolute viscosity : 2.27*10^{-5} Pa.s (μ)
- Bulk velocity : 0.1 m/s (V)
- Channel height: 1 m – The equivalent hydraulic diameter for an infinitely large channel is twice the channel height that is 2m.

The above fluid density, viscosity and velocity and hydraulic diameter provides a Reynolds number of 14 000.

3.1.2_Model I: channel with a "short" width and an obstacle at inlet

The channel uses an obstacle at inlet (actually, two obstacles, one on the upper wall and one on the lower wall for symmetry purposes) to generate turbulence at inlet. This obstacle is located at a relatively short distance from the inlet (approx. 0.3 m). The channel is 3 m long to allow some development of the flow downstream the obstacle. The channel width is 0.226 m to provide some degree of interaction between the turbulent structures over a set of riblets.

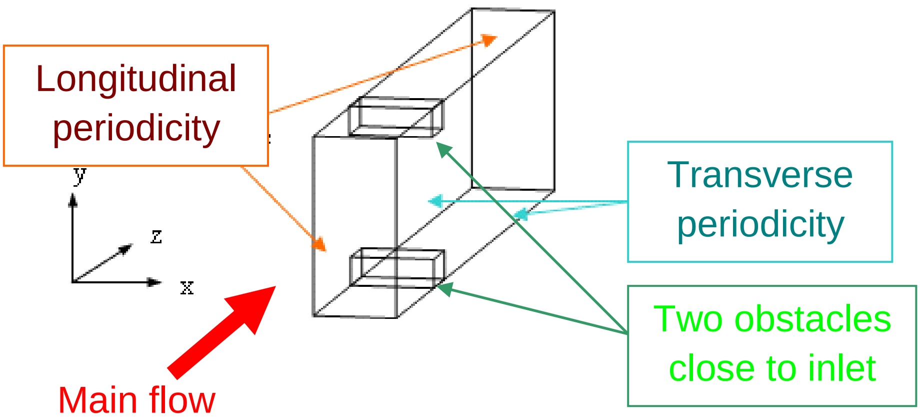

Figure 3.1.2.1 – Channel used for flow simulation on two dimension riblets

Riblet dimensions are defined from the friction velocity: $V^* = V\sqrt{C_f/8} = 6.026*10^{-3}$ m/s where V is the bulk velocity and C_f the friction factor. For a low Reynolds number, the friction factor, $C_f = 0.316/\mathrm{Re}^{0.25}$ with $C_f = 0.029$ for *Re*=14 000.

The friction length is $l_f = \mu/V^*\rho = 2.35*10^{-3}$ m.

From numerous published works (Bechert D.W. – 1997), two dimension knife blade riblets present an optimum performance when their height and their width are equal, respectively, to 8 and 16 times the friction length. This is currently written as, dimensionless height $h^+ = 8 = h / l_f$ and dimensionless width $s^+ = 16 = s / l_f$.

Consequently *h* = *0.0188* m and *s* = *0.0376* m. This calculation indicates that six riblets are contained in the channel width which may be found sufficient for checking the suitability of the LES code.

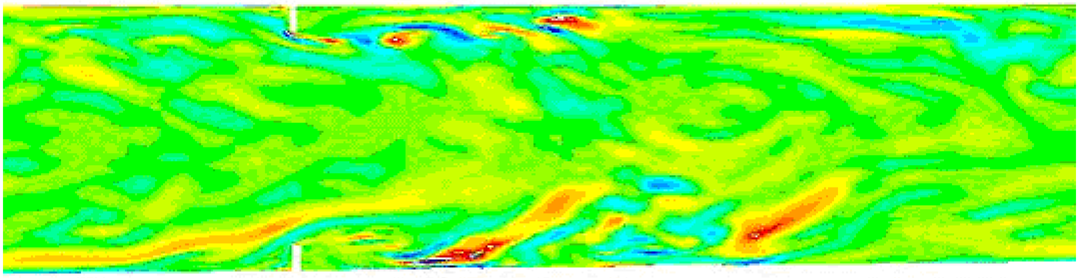

Figure 3.1.2.2 – Typical iso-velocity contours in a turbulent channel with fluid velocities varying from - 2 m/s (blue) to + 2 m/s (red) through 0 m/s (green). Upper and lower walls are, respectively, at the top and the bottom of the figure.

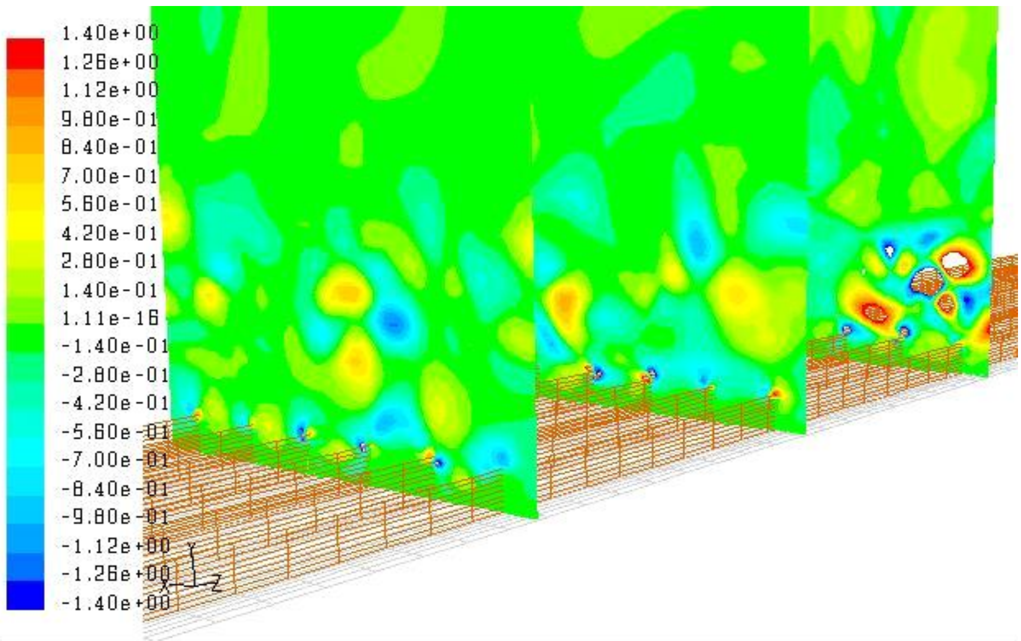

Figure 6.1.4 – Typical iso-velocity contours in a turbulent channel with fluid velocities varying from – 1.4 m/s (blue) to + 1.4 m/s (red) through 0 m/s (green). The lower wall is made of two dimension riblets of the knife blade type.

This model has been used with some degree of satisfaction in the case of a forced turbulence situation (obstacle at inlet) finding the order of magnitude of the drag reduction provided by a two dimension riblets, however, some disadvantages were found from this model :

- a relatively long length is required to stabilize the forced turbulence produced by the two obstacles,

- a larger width would be required when simulating three dimension structures considering their overall shape in the transverse direction.
- a larger width is also required when simulating two dimension structures to prevent too close interference / correlation between the turbulent structures located at the right and left sides of the channel and also for a better representation of the low speed streaks. In summary, a larger width is required for a better representation of the turbulence evolution.

As a consequence, a model with a larger width, a longer length and without any obstacle into the channel was tested.

3.1.3_Model II: channel without any obstacle – Noise generation

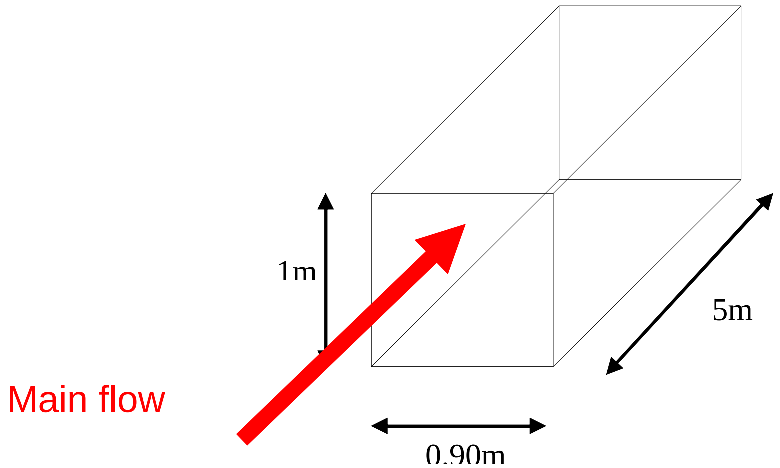

Figure 3.1.3.1 – Channel II with extended width and length. This channel does not include any obstacle, the turbulence being generated from noise injected randomly into the channel.

In model I, the channel width is roughly equal to 100 times the friction length which, represents, according to the turbulence literature, more or less the space occupied in the transverse direction by a pair of low speed streaks (LS streaks are usually coupled, propagating in the longitudinal direction in contra rotative motions). In this second channel, the width is extended from 0.226 to 0.9 m allowing the space for 4 to 5 pairs of low speed streaks. The number of simulated riblets is then 26.

In model I, the channel length is roughly equal to 1300 times the friction length which represents, according to the turbulence literature; more or less the space occupied in the longitudinal direction by 2.5 pairs of low speed streaks. In this second channel, the length is extended from 3 m to 5 m allowing the space for 4 to 5 pairs of low speed streaks.

With the present flow simulation, the calculation is first started in RANS mode to provide a relatively representative flow situation then restarted in LES with noise generated randomly into the channel. Noise generation permits turbulence generation. After a certain time, noise generation is progressively stopped and turbulence entertained due, to some extent, to the flow recirculation from the channel outlet to the inlet.

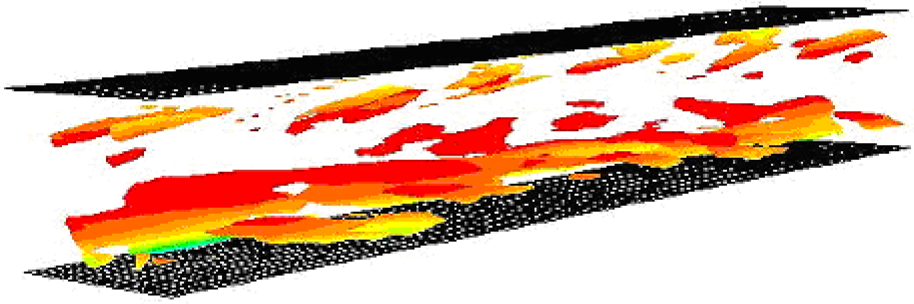

*Figure 3.1.3.2 - Turbulent structures after **300 seconds** of calculation - iso contours for a vorticity factor Qv=3,25.10-5 s^{-2}*

*Figure 3.1.3.3 - Turbulent structures after **700 seconds** of calculation - iso contours for a vorticity factor Qv=3,25.10-5 s^{-2}*

It has been noticed that after a certain time, the turbulence level tends to reduce letting the flow reaching a laminar flow situation. This may be seen on figures 3.1.3.2 and 3.1.3.3 where the volume occupied by the vorticity of a given level (parameter measuring to some extend the turbulence level) has considerably reduced with the time increasing from 300 to 700 seconds.

Finally, this model II was given up. It is not fully certain at this time, whether the turbulence damped because the Reynolds number was not large enough or if the mesh size was too big.

3.1.4_Model III: channel with a "large" width and an obstacle at inlet

The calculation restarted on the basis of model I but bringing three major modifications :

- the obstacle is located at the inlet / outlet interface to increase the stabilization length
- the channel width and channel length are increased to the values adopted to channel II for allowing more low speed streaks into the channel volume.

The calculation has been performed for three flow cases: 80, 100 and 120 % where 100 % represents the nominal flow case for which the two dimension structures have been designed.

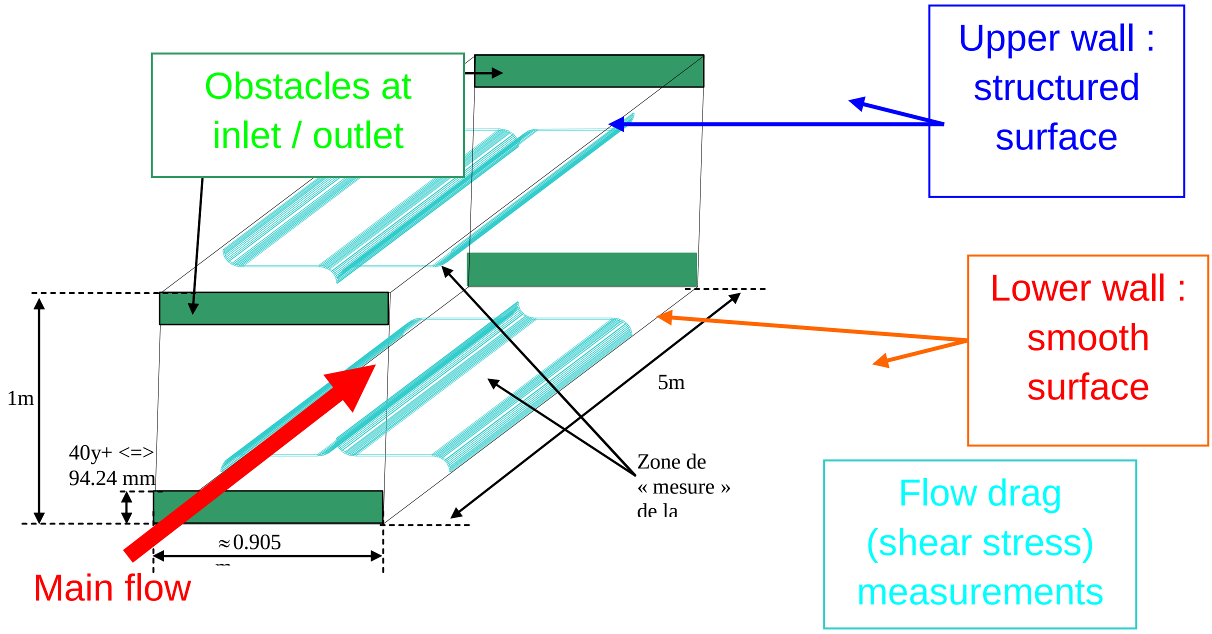

Figure 3.1.4.1 – Channel III with extended width and length including obstacles at inlet / outlet interface. Shear stress measurements made at the centre of the channel.

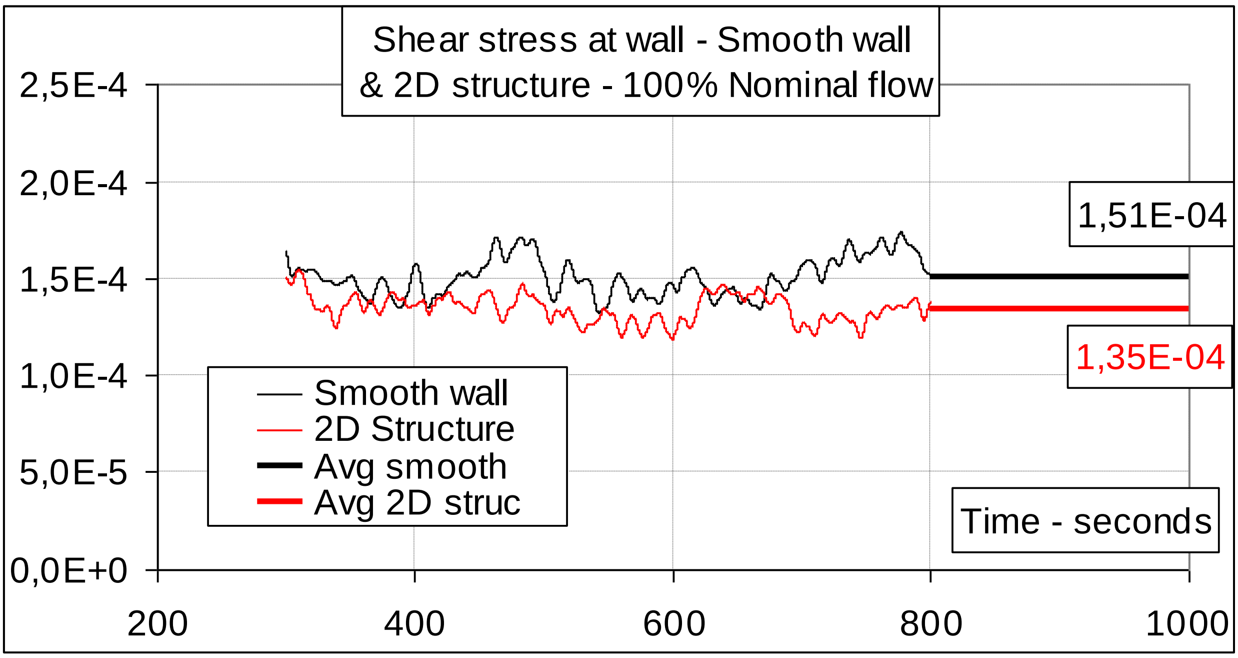

Figure 3.1.4.2 – Shear stress (Pascal) at smooth and structured walls. Case of 2D structures and 100 % flow (nominal flow).

Flow simulation results, corresponding to the 100 % flow case (*V=0.1 m/s*), are presented on figure 3.1.4.2 providing the shear stress variation versus the time for the two walls: smooth (upper wall) and structured (lower wall). The corresponding flow drag reduction provided by the structured wall is represented on figure 3.1.4.3 versus the time. It is of the order of 10 %, corresponding fully to the results provided by the literature.

The flow drag reduction provided by the 2D structure (knife blade type) and with the flow varying from 80 to 120 % is presented on table below. It can be seen from these three calculations that the average drag reduction is of the order of 10 % confirming the results presented in various papers (flow simulations or experiments).

Flow relative to nominal flow	**80 %**	**100 %**	**120 %**	**Average**
Flow drag reduction - percent	**11.7**	**10.4**	**9.3**	**10.4**

Flow drag reduction provided by 2D structures (knife blade) for three flow conditions.

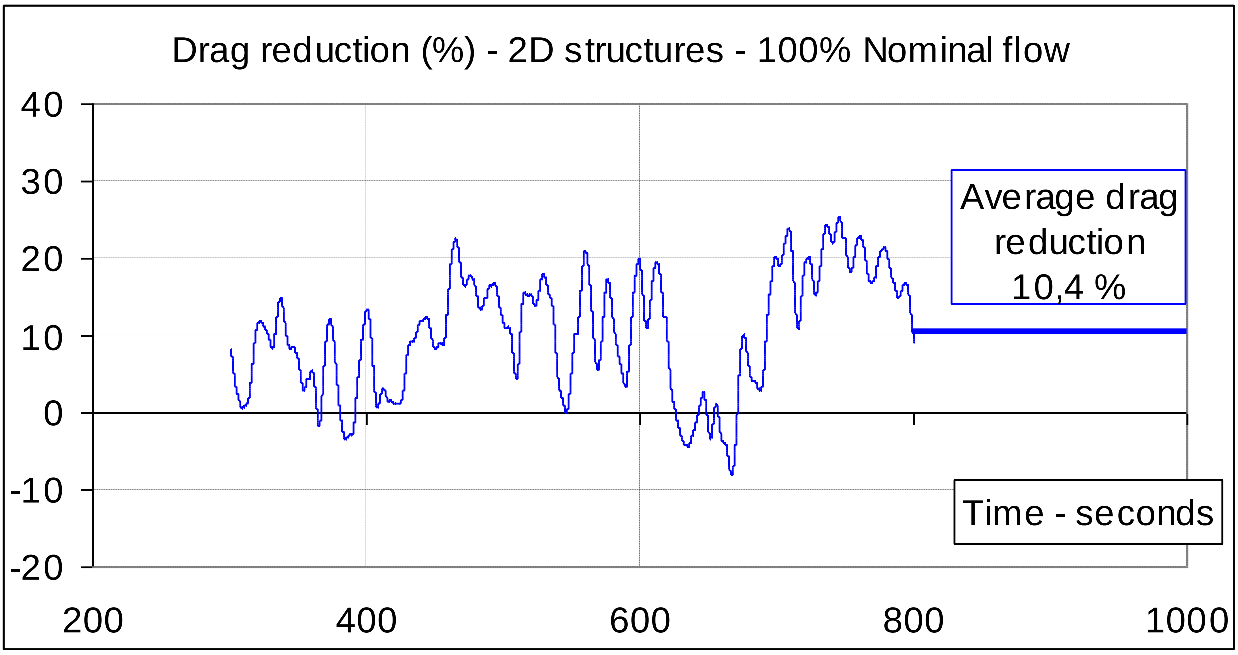

Figure 3.1.4.3 – Flow drag reduction provided by the structured wall relative to the smooth wall. Case of 2D structures and 100 % flow (nominal flow).

3.2_A three dimension structured surface combining two flow drag reduction mechanisms

3.2.1_Selection of a 3D structure – principle of operation

In section 2, the flow drag reduction provided by a wall oscillating transversally to the main flow direction was analysed for two purposes:

- to validate a LES code in the case of a flow situation with a complex boundary layer near a channel wall i.e. a three dimension displacement of the boundary layer
- to transfer, if possible, the flow drag reduction mechanism provided by a transverse oscillating wall to a fixed wall.

To transfer the principle of a transverse oscillating wall to a fixed wall, several types of structures have been considered and the following retained: ***Structures with a pattern corresponding to the required fluid displacement near the wall (transversal oscillation), ranged at small intervals and with a height of the same order of magnitude than the boundary layer thickness (micro structures)***. These structures could guide the flow transversally in the wall vicinity and with a relatively small increase in friction losses compared to a smooth wall (the largest part of these micro structures is embedded into the viscous layer). In addition, if these structures are designed like riblets that is with optimum dimensions regarding their height and width, it could result a synergetic effect in the two flow drag reduction mechanisms.

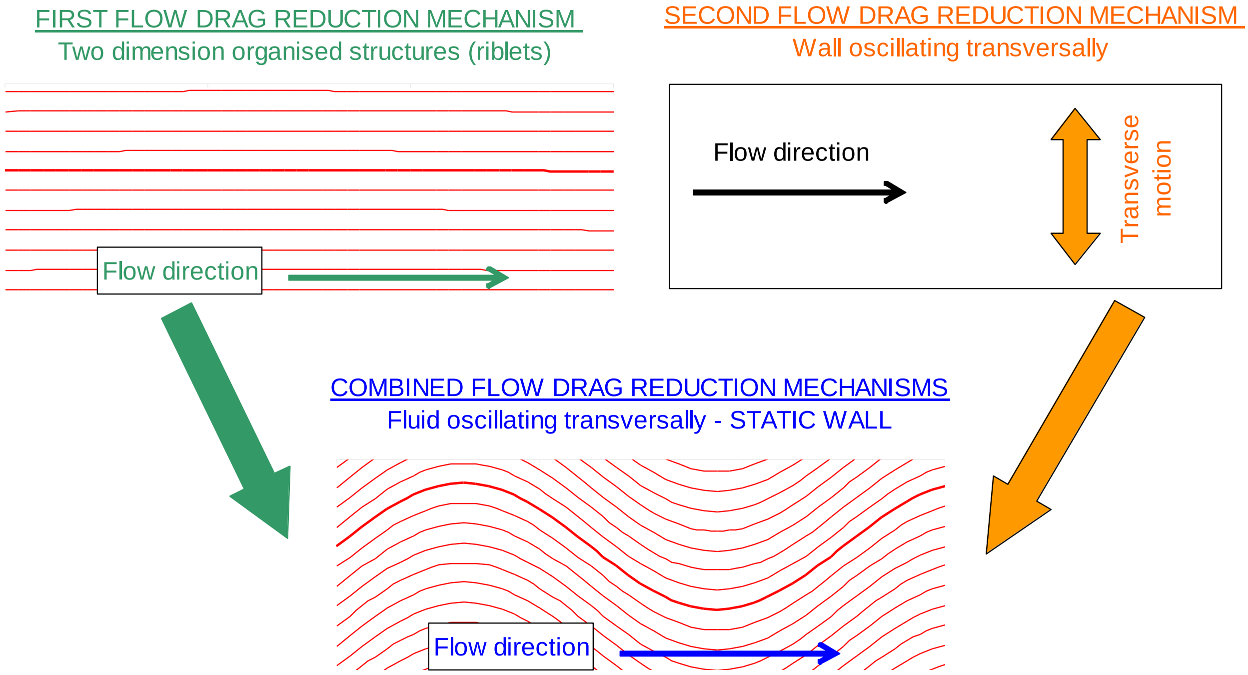

Figure 3.2.1 – Design of a three dimension structured surface combining the benefits of two flow drag reduction mechanisms: a two dimension structured surface and the transverse motion of an oscillating plate.

3.2.2_Determination of the 3D structure parameters

Four parameters need to be determined: the riblet height and width on one side and the oscillation length and amplitude on another side.

The riblet height and width are defined exactly as for a conventional two dimension structure.

The period (or length) of the oscillation of the three dimension structure is defined similarly to the case of a wall displacement. According to many publications (CHOI K.S., JUNG W. et al., LAADHARI F et al., QUADRIO M. and SIBILLA S., QUADRIO M. and RICCO P.), a maximum flow drag reduction is obtained when the dimensionless period T^+ is close to 100.

with $T^+ = T\dfrac{V_{friction}^2}{\nu}$ and $V_{friction} = V^*$.

Considering two oscillations over the channel length, each oscillation is 2.5 m long and the time for the flow to cover that length is 25 seconds. On this basis $T^+ = 64$.

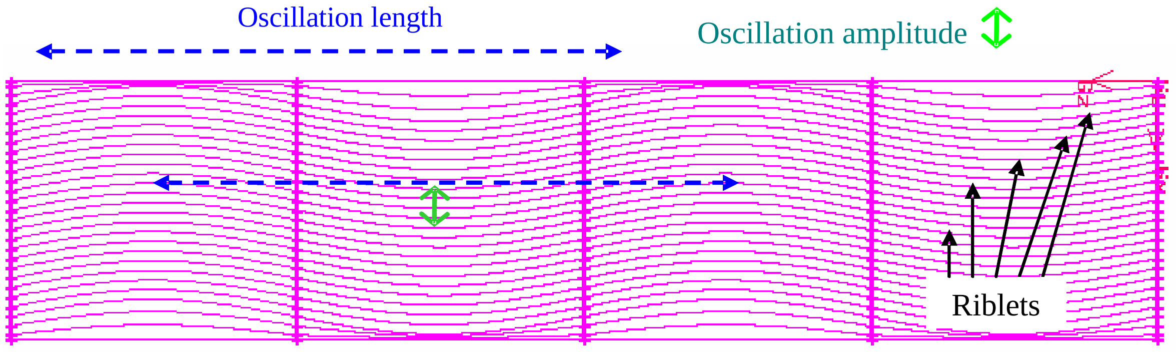

Figure 3.2.2.1 – The three dimension structured surface analysed in the present study showing the crests of the riblets making sine waves in the flow direction.

The amplitude of the oscillation of the three dimension structure cannot be defined similarly to the case of a wall displacement. Most publications give information on flow drag reduction provided by oscillating plates disregarding the energy balance. In most publications, it is shown that the flow drag continues to reduce as the oscillating amplitude (also oscillating velocity) increases. It is fairly obvious that the input energy to the system increases as the oscillating amplitude / velocity increases (for a given period / frequency). This was pointed out by BARON A. and QUADRIO M who determined the effectiveness of the system comparing the energy provided to the system with the energy saving corresponding to a flow drag reduction.

The oscillation shape is defined by $z = z_0 Sin(2\pi t / T) = z_0 Sin(2\pi x / T / V)$ where z and x are, respectively, the transverse and the longitudinal coordinates.

The flow near to the wall, following exactly the structure - wave profile, the transverse velocity of the fluid near to the wall is $z' = z_0 2\pi / T / V \cos(2\pi x / T / V)$. The maximum wave angle is equal to $arc\tan(z'_0) = arc\tan(z_0 2\pi / T / V)$

In most publications, the dimensionless transverse displacement is defined as $Z^+ = z_0 \frac{V_{friction}}{\nu}$ and the dimensionless transverse velocity $W^+ = Z^+ / T^+$

In the present case the dimensionless transverse velocity was selected to 0.44 corresponding to an oscillation amplitude of 67 mm and a maximum wave angle of 9.6 degrees.

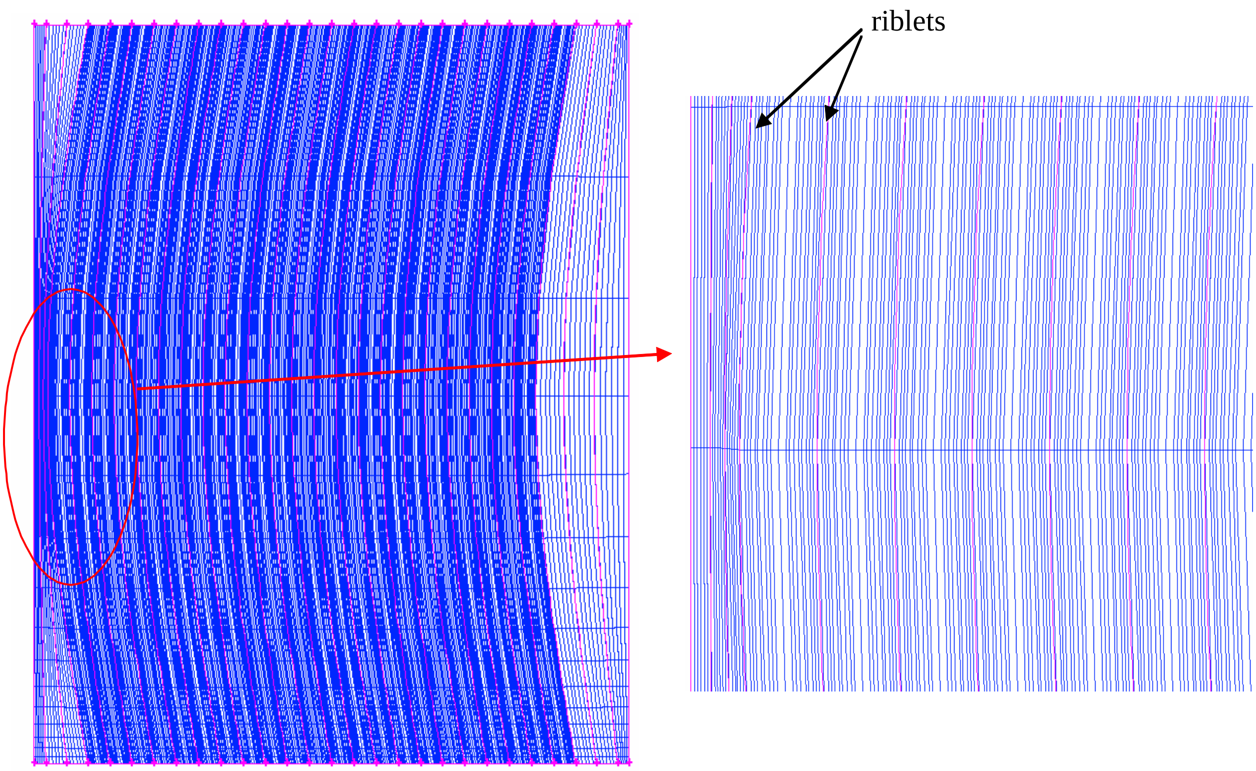

Figure 3.2.2.2 – Meshing of the three dimension structured surface.

3.2.3_Flow simulation results

Iso velocity contours are presented on figures 3.2.3.1 in three cases: a) top, for a smooth surface, b) middle, for a 2D structured surface and c) bottom, for a 3D (2D with oscillation) structured surface.

The shear stress at smooth and 3D structured walls are represented, in the case of the nominal flow, on figure *3.2.3.2* together with the relative flow drag reduction provided by the 3D structured surface (figure *3.2.3.3*).

Flow relative to nominal flow	**80 %**	**100 %**	**120 %**	**Average**
Flow drag reduction - percent	**22.7**	**17.3**	**16.9**	**19.0**

Table 3.2.3 Flow drag reduction for three flow conditions provided by the 3D structure : 9 deg, 67 mm amplitude.

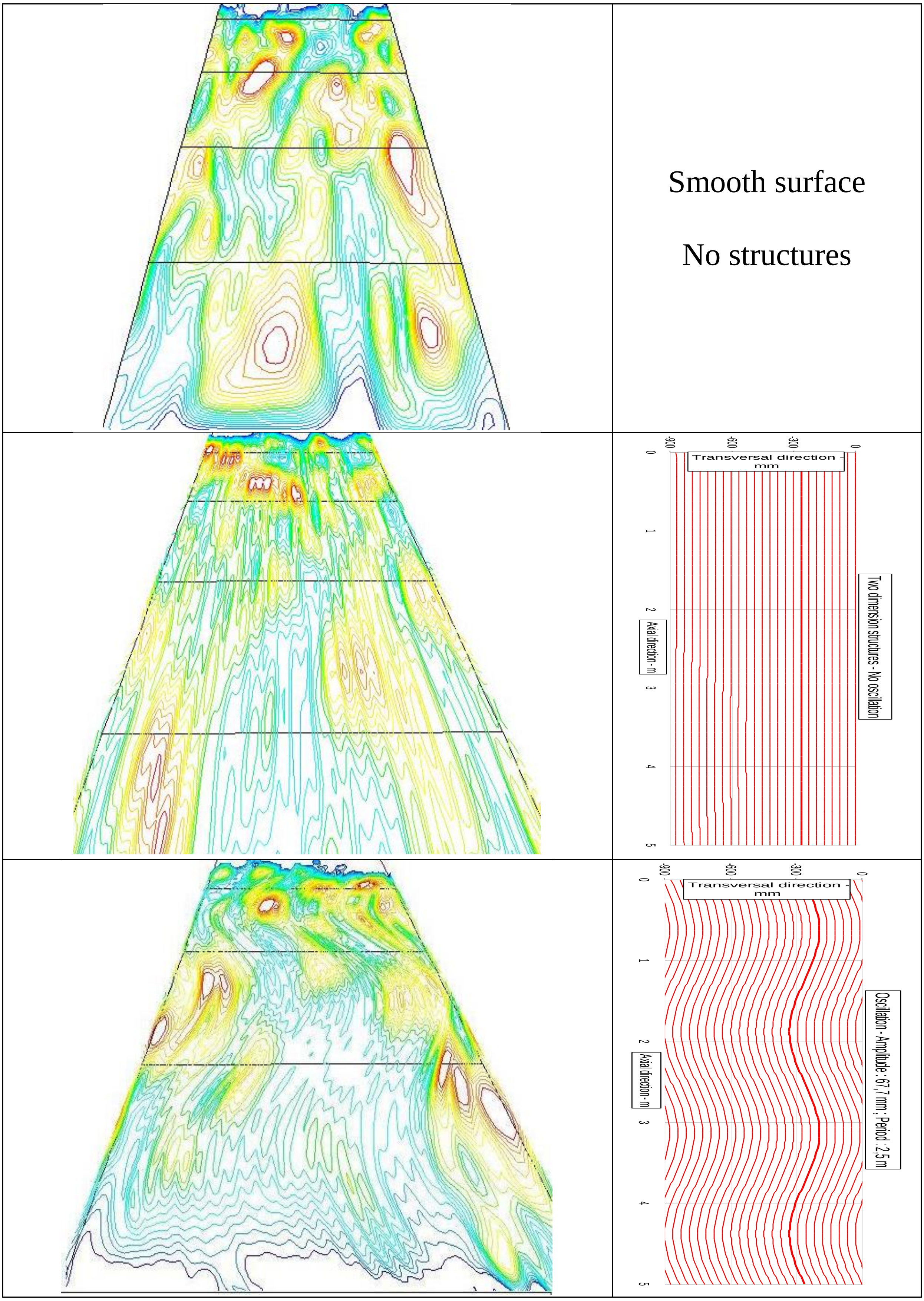

Figure 3.2.3.1 Left – Iso longitudinal velocity near channel wall for smooth (top), 2D (middle) and 3D structured (bottom) surfaces. Right – Corresponding structures.

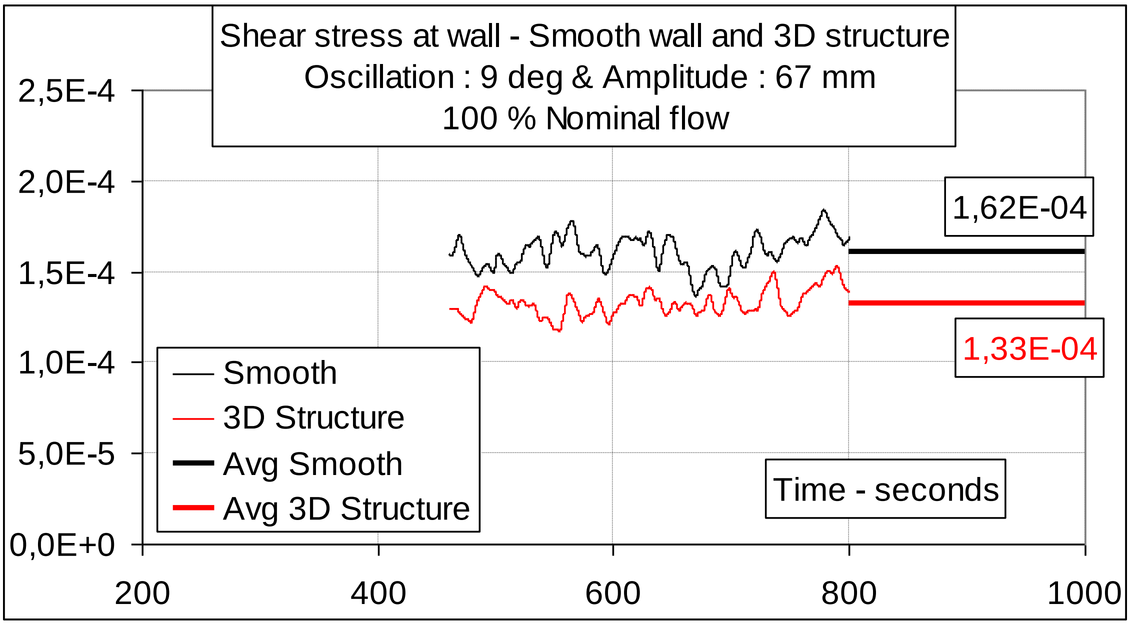

Figure 3.2.3.2 – Shear stress (Pascal) at smooth and structured walls. Case of 3D structures with 2.5 m oscillation length and 67 mm amplitude - 100 % flow case (nominal flow).

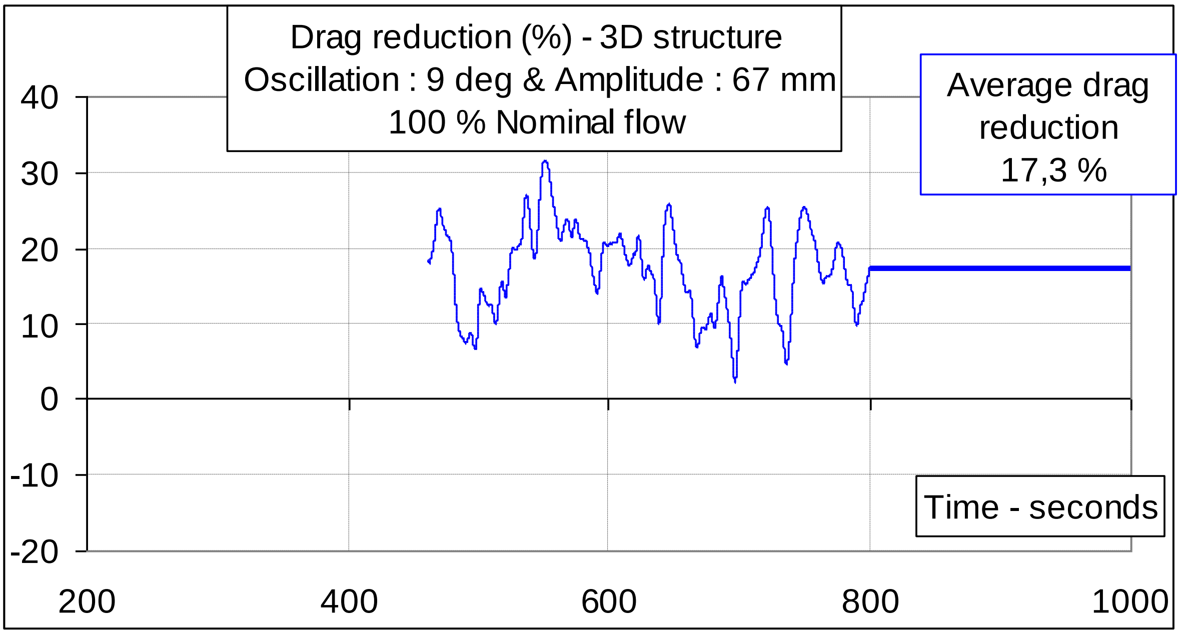

Figure 3.2.3.3 – Flow drag reduction provided by the structured wall relative to the smooth wall. 3D structures_ 2.5 m oscillation length_67 mm amplitude (9 deg.) - 100 % flow case.

3.3_Parametric study of the three dimension structure

3.3.1_Change in the oscillation amplitude

The oscillation amplitude has been increased from 67 to 121 mm keeping the oscillation length constant (2.5 m). Compared to the above case (67 mm amplitude), the average flow drag reduction is slightly smaller 14.8 instead of 19.0 % (table 3.2.3 and figure 3.2.3.2).

Flow relative to nominal flow	**80 %**	**100 %**	**120 %**	**Average**
Flow drag reduction - percent	**13.9**	**15.7**		**14.8**

Table 3.3.1 – Flow drag reduction - 3D structure: 17 deg, 121 mm amplitude.

3.3.2_Change in the oscillation length

The oscillation length has been reduced from 2.5 m to 1.67 m (2 to 3 oscillations over 5 m). Compared to the basic oscillation configuration (67 mm amplitude), the average flow drag reduction is considerably smaller 8.7 % instead of 19.0 % (table 3.2.3 and figure 3.2.3.2).

Flow relative to nominal flow	**80 %**	**100 %**	**120 %**	**Average**
Flow drag reduction - percent	**7.4**	**6.7**	**12.1**	**8.7**

Table 3.3.2 – Flow drag reduction - 3D structure: 9 deg, 45 mm amplitude

3.3.3_Summary of the test results

Characteristics (absolute and dimensionless values for the oscillation period, displacement and velocity) of the three 3D structures (cases 1 to 3) with the corresponding average flow drag reduction obtained in the 100% flow case are presented on table *3.3.3*.

	Case 1	**Case 2**	**Case 3**
Nb of oscillations over 5 m	2	2	3
Oscillation length	2.50 m	2.50 m	1.67 m
Dimensionless period T^+	64	64	43
Oscillation amplitude	67 mm	121 mm	45 mm
Dimensionless amplitude Z^+	28	51	19
Max. transverse velocity	0.168 m/s	0.304 m/s	0.169 m/s
Dimensionless velocity W^+	0.44	0.80	0.44
Max oscillation angle	9.6 deg	16.9 deg	9.6 deg
Max transv. acceleration	0.42 m/s^2	0.76 m/s^2	0.64 m/s^2
Z^+/ T^{+3}	1,10E-4	1,99E-4	2,48E-4
Average drag reduction	**19.0 %**	**14.8 %**	**8.7 %**

Table 3.3.3 – Characteristics of the three 3D structures analysed in the flow simulation study with corresponding flow drag reduction.

The flow drag reduction provided by the above 3D structures may be broken in two parts: firstly, the one provided by the riblets and, secondly, the one resulting from the transverse oscillation (figure 3.3.3.1).

It may be seen that in the first two cases (dimensionless period = 64 - relatively long oscillations) the drag reduction provided by the oscillation alone approaches 10 %. From an oscillation amplitude equal to 67 mm, as the amplitude tends to 0, the drag reduction provided by the oscillation tends towards 0 (the limit of the 3D structure being the 2D structure). Similarly, when the amplitude becomes too large, the crest of the sine wave tends to make an obstacle to the flow and to limit the flow drag reduction.

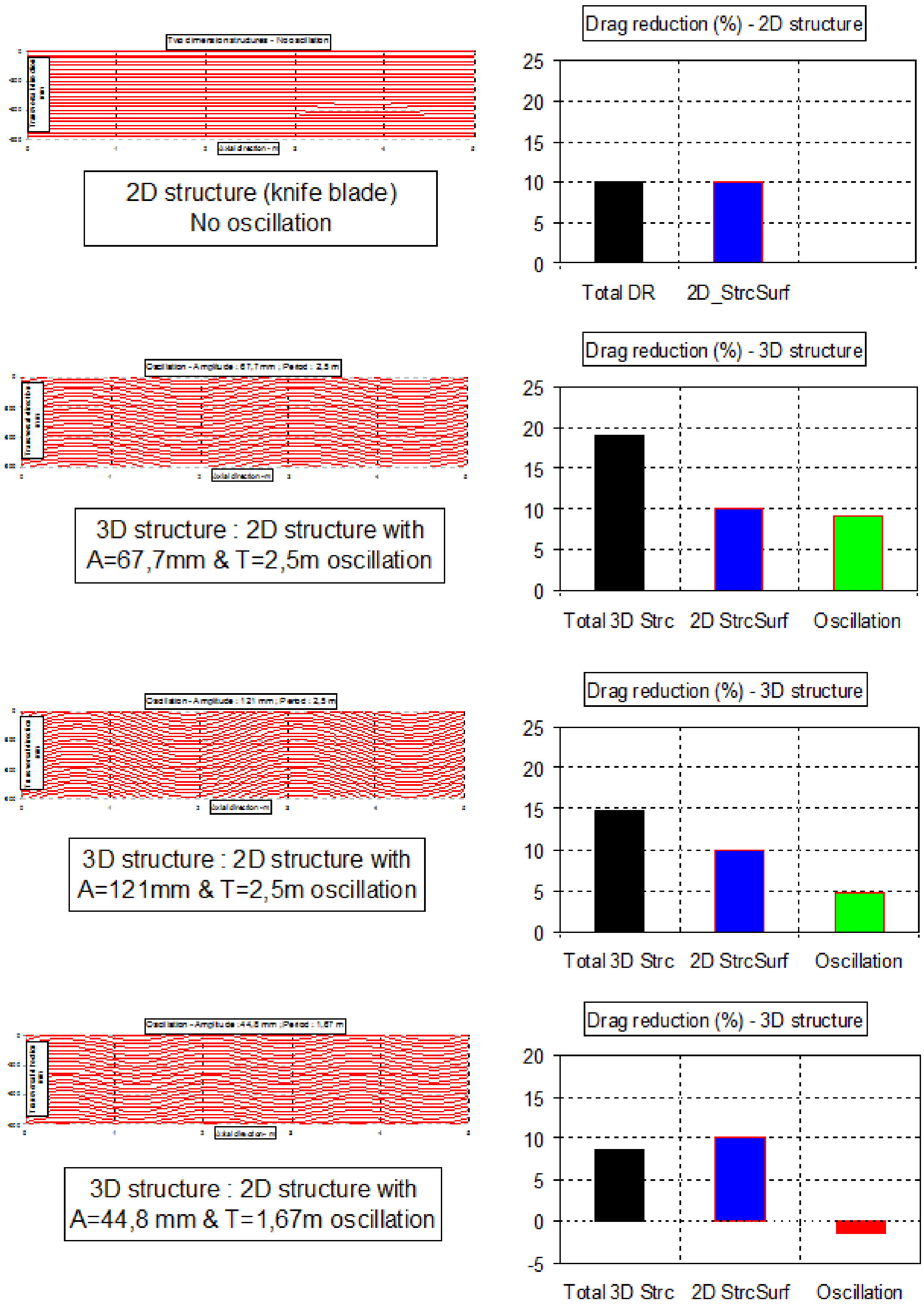

Figure 3.3.3.1 – A 2D structure and three types of 3D structure – Geometrical shapes (Left side) – Flow drag reduction (right side) provided by 3D structures (black), part due to the 2D structure (blue) and part due to the oscillating wave (green or red).

In the third case (dimensionless period = 43 - relatively short oscillation duration), despite a positive total flow drag reduction, the drag reduction provided by the oscillation itself is negative. This may indicate that if the oscillation period is not long enough, the turbulent flow near the wall is not given enough time to achieve full stabilisation. In other words, an oscillation with a too short period may provide more agitation to the flow near the wall than a proper stabilisation.

The flow drag reduction provided by the oscillation alone was analysed on this type of consideration and more particularly by considering the drag reduction versus the transverse excitation. The transverse excitation may be defined by the maximum acceleration reached by the sine wave divided by the time required to reach this acceleration (figure 3.3.3.2). It has to be noted that the time is also proportional to the period length. In other words, the excitation parameter may be defined by the maximum acceleration divided by the wave length or the time required to reach this acceleration (Z^+/ T^{+3}). From figure 3.3.3.2, it is suggested that a minimum agitation is required to stabilize the boundary layer flow (flow drag reduction) and that above a threshold the trend reverses providing a negative drag reduction when the agitation is too large.

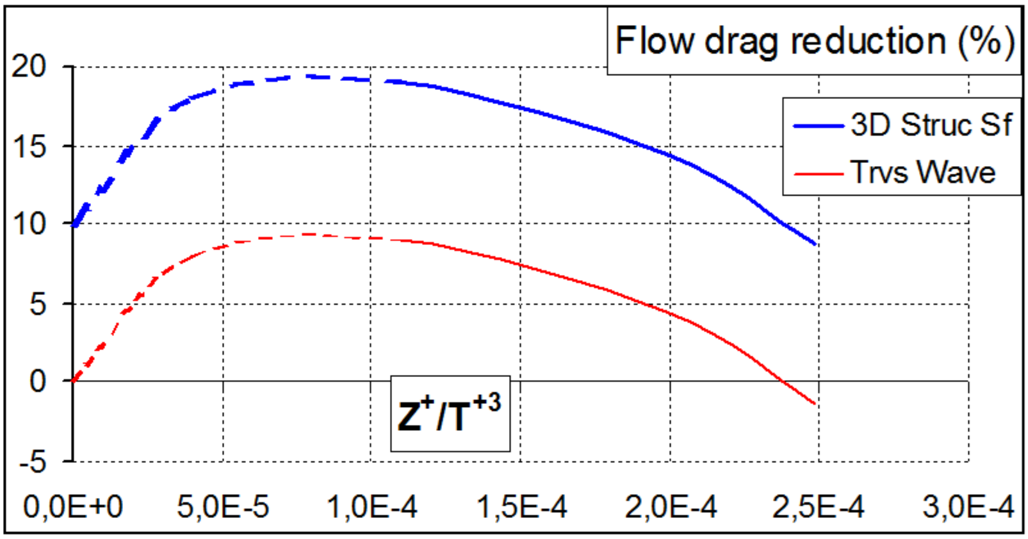

Figure 3.3.3.2 – Flow drag reduction provided by the 3D structure and the transverse wave versus an excitation parameter defined as the transverse amplitude divided by the cube of the oscillation duration (or length). These last two are dimensionless parameters.

3.4_Application to industrial cases – gas transport

3.4.1_Generalization to any turbulent flow case

Four parameters need to be determined to define the three dimension structure analyzed in above sections and to obtain a significant flow drag reduction.

The dimensionless riblet height	$h^+ = h / l_{friction} = 8$	Note 1
The dimensionless riblet width	$s^+ = s / l_{friction} = 16$	Note 1

The dimensionless oscillation period $50 < T^{+} = T\dfrac{V_{friction}^{2}}{\nu} < 100$ Note 2

The dimensionless oscillation velocity $W^{+} = Z^{+} / T^{+}$ Note 2

Where, *h* and *s* are the micro structure height and width,

the friction length : $l_f = \mu / V_{friction}\rho$ with μ and ρ the fluid viscosity and density

the friction velocity : $V_{friction} = V\sqrt{C_f / 8}$ with *V* the bulk (average) fluid velocity

and the friction factor calculated from Blasius or Prandtl equations depending on the magnitude of the Reynolds number.

Note 1: concerning the dimensionless height, 8 is an optimum value for a knife blade riblet. It is slightly greater for triangular and "U" shape riblets. The optimum value for the dimensionless width does not change very much with the riblet type.

Note 2: optimum values for the dimensionless oscillation period and the dimensionless transverse velocity could not be determined very precisely due to the difficulty in carrying out a parametric study with a LES code. Nevertheless, a flow drag reduction of 20 % could be reached with *T+=64* and a maximum wave angle of 9.6 degrees.

It is more likely that the maximum drag reduction has not been reached yet. Further flow simulations would be required around this set of values to determine the maximum drag reduction which could be provided by this type of three dimension structure.

3.4.2_Application to a gas pipeline

The sizing of a three dimension structure has been performed on the basis of the following gas transport conditions:

- Gas properties: natural gas with a molecular weight of 17
- Pipe diameter: 1 m
- Gas velocity at pipeline inlet: 4 m/s
- Pipe pressure varying from 80 bar at inlet to 40 bar at outlet
- Temperature constant along the pipe: 27 °C

The gas characteristics (compressibility factor, density and viscosity) and the gas velocity were calculated for several pressure conditions. Their variation is represented on figure 3.4.2.1.

- The compressibility factor varies from 0.877 at inlet to 0.934 at outlet
- The dynamic viscosity varies from 1.28E-5 to 1.17E-5 kg/m/s
- The gas velocity varies from 4 to 8.52 m/s
- The Reynolds number varies from 1.95E7 to 2.12E7 (variation mostly due to the viscosity change with the pressure)

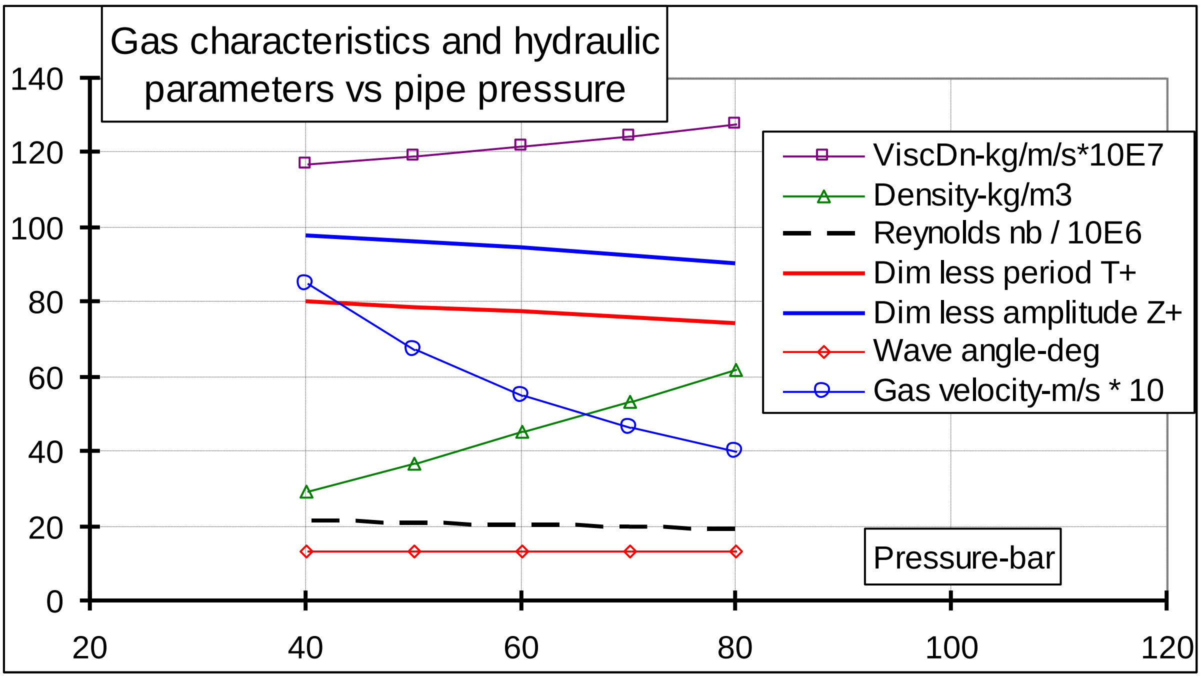

Figure 3.4.2.1 – Flow conditions and 3D structure characteristics versus pipeline pressure.

For this application, a three dimension structure was selected with the following characteristics: a wave length of 4 mm with an amplitude of 0.15 mm. On this basis:

- the dimensionless period T+ varies from 74 to 80 which is of the same order of magnitude than the value found for a 3D structure adapted to a Reynolds number of 14000.
- the dimensionless amplitude Z+ varies from 90 to 97.
- the dimensionless transverse velocity Z+/T+ is constant and equal to 1.22.
- the maximum wave angle is 13.3 degrees which is also of the same order of magnitude than the one found for a 3D structure adapted to a Reynolds number of 14000.

<u>Conclusion for this paragraph</u>: The small variations, along the pipeline, of the dimensionless period T+ and amplitude Z+ indicate that the same three dimension structure (type, geometry and dimensions) may be kept from pipeline inlet to outlet.

4_Conclusion

A LES Code could establish the drag reduction provided by a plate oscillating transversely to the main flow direction. Maximum drag reduction is obtained for a dimensionless period of 100. In this case, the drag reduction varies considerably with the amplitude of the oscillation (disregarding the input energy brought to the plate).

Two dimension riblets of the knife blade type provides a maximum drag reduction of the order of 10 %. The same result was found with a RANS code (see corresponding Web site page) and a LES code (above section 3.1).

Three dimension structured surfaces combining the above two flow drag reduction mechanisms (2D riblets and transposed transverse flow oscillation) provide a drag reduction of the order of 20 %. The maximum drag reduction was achieved for a dimensionless period of 100 and a maximum angle of the transverse oscillation of the order of 10 degrees.

In the case of gas transport in a pipeline with inlet and outlet pressure varying in a large ratio, the following parameters would change very little: the Reynolds number, the 2D riblet sizes, the dimensionless period, the dimensionless amplitude and the maximum angle of the structure oscillation.

Considering the shape of these 3D structures, they could be manufactured in using the same process as the one anticipated for the 2D riblets. See corresponding Web site page.