EFFECT OF STATIONARY VORTEX TO HEAT TRANSFER ON DELTA WING

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Abstract

Based on the persistence theory, the vortex is considered stationary, if its translational velocity is less than its rotational velocity. This physically means the vortex tend to stay in one place than move around. In heat transfer application, the stationary vortex helps increase heat convection by continuously bringing in fresh fluid to the interface, and taking out the heated fluid, in the same manner as a heat exchanger. Prior researchers had worked on the grooved plate, and obtained promising results. Here, we applied the principles to the heat transfer on the delta wing, where two apex vortices are distinctively present on the suction side of the wing. Those apex vortices are apparently straight and stationary. Any deviation from straightness by any kind of perturbation causes the apex vortices to be wavy, and hence, non-stationary. Then, according to the persistence theory, any kind of perturbation to the apex vortex will decrease overall convective heat transfer on the delta wing. Preliminary experiments in both wind and water tunnels show that, this is indeed true. This paper explains from basic principles to experiments.

1. Introduction

Recently Breidenthal (Balle and Breidenthal, 2002) proposed the persistence theory, which explains the increase of heat transfer rate on the wavy wall, due to the existence of a stationary vortex. Their results show the dramatic increase from the turbulent to that of laminar values. In this paper, we investigate further to the stationary pair of vortices on the delta wing. It is well known that for the delta wing at high angle of attack, the flow separated on the suction side of the wing forms a pair of vortices, which appears to be stationary in location. Note that, this pair of vortices can burst downstream and becomes vortex breakdown, shown in Fig. 1. Srigrarom has been studied on suppression this vortex breakdown, by means of changing the path of the upstream vortex (Srigrarom, 2001). The perturbation effectively changes the vortex to be non-stationary, as shown in Fig. 1. Therefore, in view of the persistence theory, the heat transfer (and hence, momentum transfer or drag by Reynolds' analogy) would be different. Here we have conducted simple experiments, described in the flowing parts, comparing the heat fluxes for the normal vortex (stationary vortex) case to the perturbed vortex (non-stationary vortex) case. The experimental results are presented in details.

2. Stationary and Non-stationary vortices

Breidenthal et al (Breidenthal, 1996, Cotel and Breidenthal, 1997 and Balle and Breidenthal, 2002) has proposed what they called "Persistence theory" to explain the connection between the stationarity of vortex and the influence on momentum and heat fluxes exchange across the surface. They defined the persistence parameter, T, based on the ratio of two velocities essential to describing the motion of a vortex: the translational velocity, V of the vortex parallel to the boundary, and appropriate measure of the vortex's azimuthal velocity, W (see figure 2). The persistence parameter, T, is simply:

$$T = k\frac{W}{V} \qquad (1)$$

where k is some constant of proportionality.

If the vorticity structure is of such a chaotic nature as to make the measurement of a representative azimuthal velocity impossible, another scheme would be to use the vortex circulation (an integral quantity) divided by a discernable vortex cross-axis width. The general idea is to recognize the relative importance of the amplitude of the velocity fluctuation due to the eddy, with respect to the mean motion tangential to the interface.

Another point worth noting here is this: while the azimuthal velocity W is unambiguous to any inertial observer, the translational component is only well defined for vortices sufficiently near to an interface, such that they can have an influence on the fluxes there (Balle and Breidenthal, 2002).

According to Breidenthal, the vortex is considered "stationary" if the azimuthal velocity is greater than the translational velocity (W > V), and considered "non-stationary", otherwise. It is this definition that dictates the apex vortices on the delta wing to be considered as stationary, in both streamwise and traverse directions. The examples are shown in Fig. 3 and 4.

In Srigrarom 2001, the author focused on suppressing the breakdown of the delta wing vortices. He introduced the idea of changing the path of the apex vortex from straight to wavy. In the current context of stationarity, this essentialy changes the stationarity of the apex vortex from stationary to non-stationary (Fig. 5).

To change the path of the apex vortex from straight to wavy (stationary to non-stationary) can be done by perturbing the vortex either in lateral or normal direction to the wing, as shown in figure 1 and 6, respectively. Alternatively, we can modify the wing, by attaching the additional strip as a vortex generator. The strip will introduce an additional vortex. The system of apex and strip-generated vortices would mutually induce, such that, each of them entangle with another are no longer straight (hence, non-stationary) downstream (Srigrarom, 2001), as shown in figure 8.

From persistence theory, the average heat convection, h, along the surface in the case of stationary straight apex vortex is supposed to be better than that in non-stationary wavy apex vortex case. This is physically because the stationary vortex helps increase heat convection by continuously bringing in fresh fluid to the interface, and taking out the heated fluid, in the same manner as a heat exchanger. This can be shown schematically, as in figure 7.

In figure 7, in the stationary vortex case, the vortex acts like a conveyer to bring out hot fluid to the freestream and bring in the cold fluid to the hot surface. Therefore, the heat transfer reaches far upto the freestream, and the heat flux is only in one direction (vertical in the diagram). For the non-stationary case, the movement of the vortex causes the surrounding fluid to move around with, and that, the heat flux is also in horizontal direction.

3. Preliminary qualitative experiments in wind tunnel, using heat lamp and heat gun

3.1 Setup

Based on the theoretical above, we design a preliminary qualitative experiment in the wind tunnel to verify. The following diagram in figure 9 shows the preliminary experiment. The experiment was conducted in the NTU large wind tunnel, with 1.2m x 0.8m x 0.8m test section. It provides steady airflow, with low turbulent level, upto 80-100 m/s (Lim & Lim, 1985). The experiment consisted of a delta wing, which was colored with black painting, and an infrared thermometer, of which the accuracy is ±1°C, for measuring the surface temperature on the delta wing. The heat source is either a heat lamp, which provided heat flux through radiation to the delta wing, or a heat gun, which provided heat flux through convection to the wing. The testing points' distribution through the upper side of the delta wing surface is presented next.

A slow airspeed, about 10 m/s, was used in wind tunnel. Steady-state convective heat transfer equation is suitable for the case and used here: (Heat flux from the heat source = heat flux through the wing = heat flux to the water).

$$q''_{input} = q'' = h(T_w - T_{ref}) \qquad (2)$$

where

q''_{input} = input heat flux from the heat source

h = average convective heat transfer coefficient

T_w = delta wing's surface temperature

T_{ref} = reference temperature = T_∞ = freestream temperature

The vortex generator was a big fin (strip) attached near to the apex of the delta wing. The sketch map is figure 11. This was to create the additional strip-generated vortices to interact with the apex vortices, and consequently, all vortices become non-stationary wavy vortices. (In the following passage, case A denotes of system with stationary vortex; case B denotes of system with non-stationary vortex.)

According to the Fig. 9, the heat flux input to delta wing was produced by the heat lamp, which directly light to the backside of the delta wing. The heat flux through the upside consisted of three basic kinds of heat transfer, conduction, convection and radiation. However, we did not care the mechanics of initial heat flux input to the system. Because the two cases we set had the same initial input through upside of the delta wing, q''_{input}. Furthermore, without heat flux through the delta wing system, both stationary case and non-stationary case had the same T_{ref}. The only difference was vortex style the air formed in two cases. That is the point we emphasize.

At the steady state, the input heat flux from the source transmitted to heat flux to the delta wing, and also to the freestream by convection. Based on the persistence theory, discussed in previous section, with the presence of the stationary vortex, the heat transfer from the wing surface to the freestream should be higher. This causes the surface temperature in case A to be smaller than the one in case B. This results in the heat transfer coefficient in case A to be larger than the case B.

In Figure 9, although it shows the set up using heat lamp as a heat source, we also performed another experiment qualitatively in the wind tunnel, using heat gun as a heat source. The heat gun was used in substitution of the heat lamp to give more control and even heat flux over the wing. The heat gun was set directly near the backside of the delta wing. All other setup were the same. Experiment results are also shown here.

In our experiment, the only quantity we measure is the upside surface temperature of the delta wing. On the delta wing, we have marked some points to measure the temperature. Even though we cannot get very correct results by infrared thermometer, the qualitative comparison can be made. It should be noted here that, before we measured the surface temperature, we need to wait the system to be steady and settled for 15 minutes.

3.2 Experimental results and analyses

From the aforementioned experiment setup, the original data obtained from the infrared thermometer are shown in Table 1. The analyzed data are shown in Tables 2 and 3.

The reference temperature, T_{ref}, is the freestream temperature, T_∞, which, for the heat lamp setup, is the wind room temperature and less than 35.92 °C $(T_{ref} = T_\infty = T_{room} < 35.92)$ and for the heat gun setup, is also the wind room temperature, but less than 37.8 °C $(T_{ref} = T_\infty = T_{room} < 37.8)$. Since, $q''_A = q''_B = q_{input}$ (same heat source in both cases), we can draw the conclusion, $h_A > h_B$. This means the stationary vortex helps better heat transfer process (higher h). These experimental results are seemed to agree with our prediction from the persistence theory.

4. Preliminary qualitative experiments in wind tunnel, using heat lamp and heat gun

From the experimental data in wind tunnel above, we conducted another experiment in the water tunnel to check the universality of the theory. The NTU water tunnel test section is 45cm x 45cm x 100cm (height x width x length). Here, the tested delta wing consisted of two-piece of 104 mm x 120 mm x 3 mm (chord length x base x height) -triangular stainless steel sheet, of which thickness was 1 mm and a triangular heater imbedded between of such two stainless steel sheets, as shown in figures 12 and 13. The delta wing's swept angle was 60 degree. The angles of attack were set at 20 and 30 degrees, and there was no yaw.

To create wavy (non-stationary) vortices, we attached two 5 mm bumps at the delta wing's apex. By the bumps' presence, the apex vortices were perturbed laterally, as shown in figures 14 and 15.

The DC power supply ran voltage = 3V, current = 4.0A to the embedded heater. In every test condition, the system was allowed to settle for minimum period of 15 minutes. Therefore, the heat transfer process could be assumed steady. By steady-state assumption, the power supply of 12 Watts became the input heat flux to the wing, which was consequently dissipated by heat convection by the flow on the wing surface. Note that, since, the delta wing's thickness is only 3 mm the heat fluxes on all its edges were negligible. Furthermore, the wing had two sides –pressure and suction, so, the heat flux to the suction side (the one in consideration) was approximately half of the total value, i.e. only 6 Watts.

In our experiments, we varied the water flow rates from 2 to 7 cms/sec, which gave the corresponding Reynolds number based on delta wing's chord length of 2300 to 8200 ($2300 < Re < 8200$). The freestream water temperature was 26.5°C, measured by a mercury thermometer; whereas the delta wing's surface temperature was measured by an infrared digital thermometer. Hereinafter is the experimental data. Note that, case A means stationary vortex and case B means non-stationary one. The results are shown in Tables 4 and 5. The Nusselt number and Reynolds number plots (*Nu* v.s. *Re*) are shown in figures 16 and 17.

We examine the vortices' effect on convective heat transfer, by considering the corresponding either heat transfer coefficient (h) or Nusselt Numbers (Nu) of both cases. From the results, shown in Table 5, figures 16 and 17, it is clear that, the stationary vortex (Case A) provides higher h and Nu than those of the non-stationary vortex (Case B) at all flow conditions and at both angles of attack. This means the stationary vortex provides better heat convection than the non-stationary vortex does, as predicted in the persistence theory.

In these delta wing in water tunnel experiments, we were also interested in establishing the empirical relationships of Nusselt numbers and Reynolds numbers of both cases (stationary and non-stationary vortices). From Table 5, at 20 degree angle of attack, we can deduce the followings:

- For stationary vortex flow case:
  $$Nu \sim 1.113Re^{0.2324} \qquad (3)$$
- For non-stationary vortex flow case:
  $$Nu \sim 1.179Re^{0.2097} \qquad (4)$$

By considering the exponents on the Reynolds number, which reflects the shape of the curves, the difference is obviously significant (0.2324 v.s. 0.2097). Although, the coefficient of the two cases, which differs by merely 6% (1.113 v.s. 1.179), the influence of the higher exponents supersede the influence of the constants. This means the stationary vortex provides the better heat convection than that of non-stationary vortex.

5. Conclusions

From all the experimental data presented in this paper, it can be seen that the convective heat transfer coefficient, h, and the corresponding Nusselt number, Nu, change noticeably in favor of the stationary vortex, in agreement with the persistence theory. Thus, we can draw the conclusion: the heat convection along the delta wing's surface in the case of stationary apex vortex is better than that in non-stationary case.

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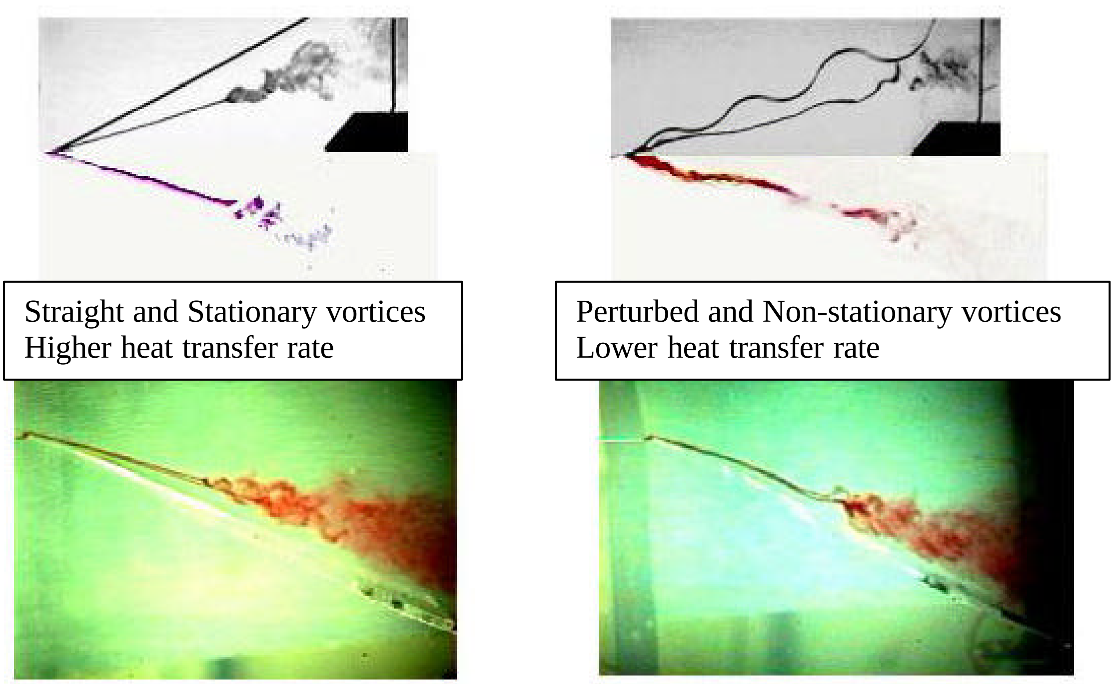


Fig 1. Vortices on the suction side of delta wing at 30°angle of attack.
Left: Delta wing without modification, showing straight and stationary vortices, which burst downstream.
Right: Delta wing with modification, showing perturbed and non-stationary vortices. (Srigrarom, 2001).

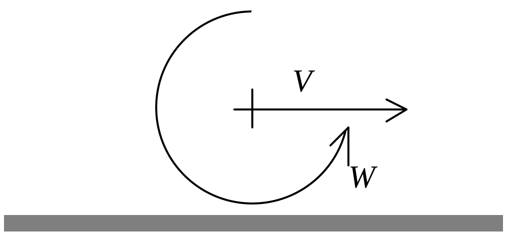


Fig. 2: Schematic of a vortex near a boundary.

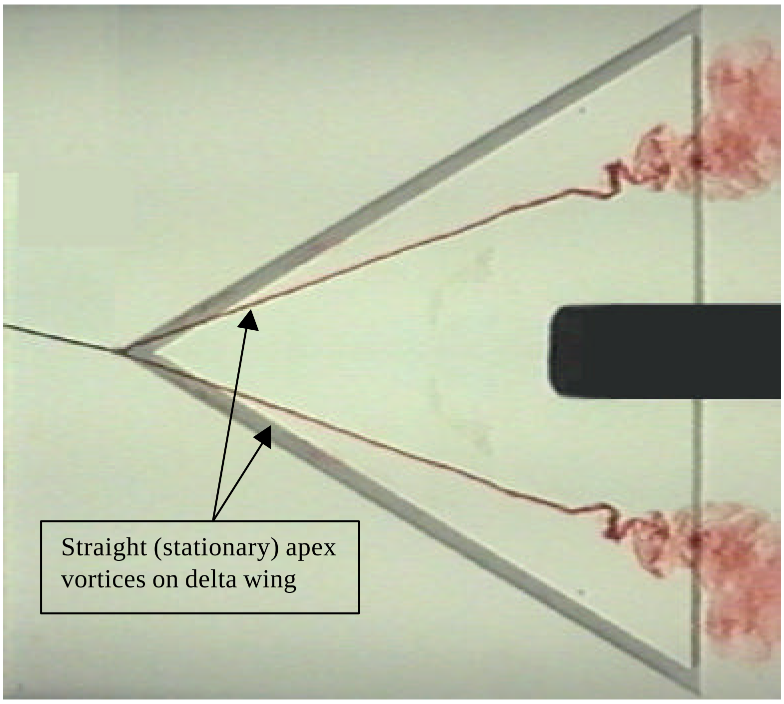


Fig. 3: Apex vortices on delta wing with 60 degree swept angle and at 15 degree angle of attack, which burst downstream. These apex vortices appear stationary in the streamwise plane (Srigrarom, 2001).

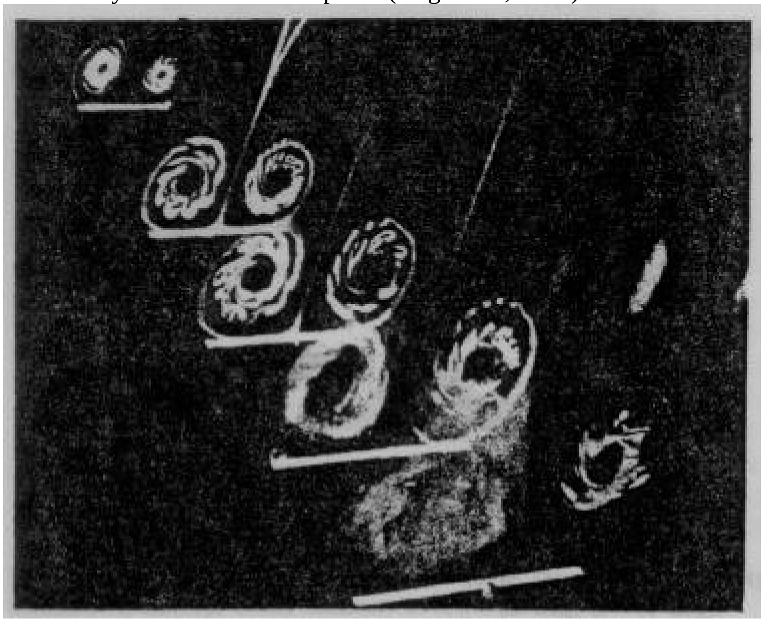


Fig. 4: The LIF image of the stationary spiraling shear layer (that causes the apex vortices to be stationary) on the cross-sectional plane (traverse direction) of the delta wing (from Payne et al, 1988)

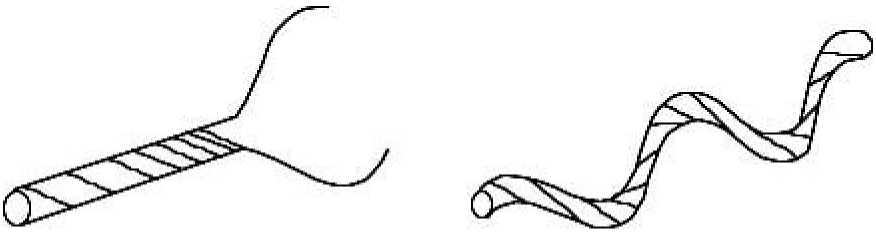


Fig. 5: Changing the path of the apex vortex from straight to wavy, essentially change the stationarity of the vortex.

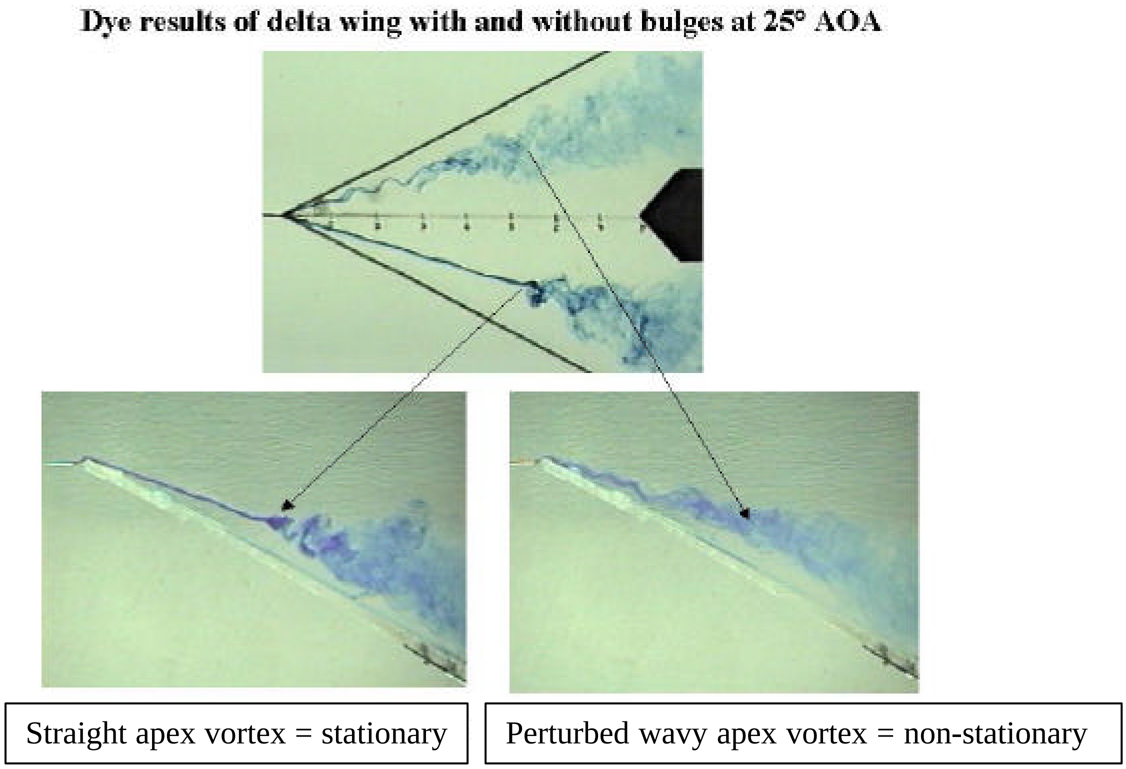


Fig. 6: Perturbation of the apex vortex in normal direction.

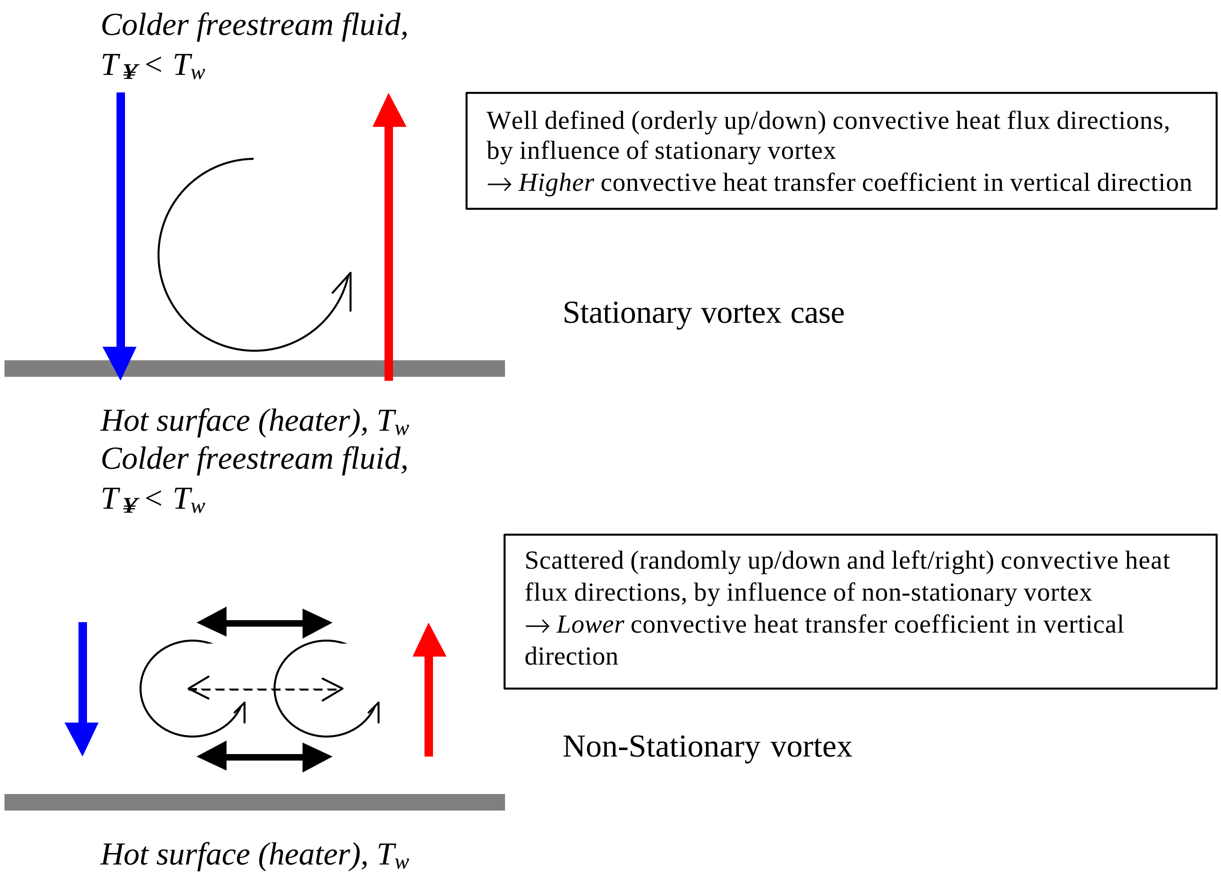


Fig. 7: Effect of vortex's stationarity on heat flux directions, and convective heat transfer in vertical direction.

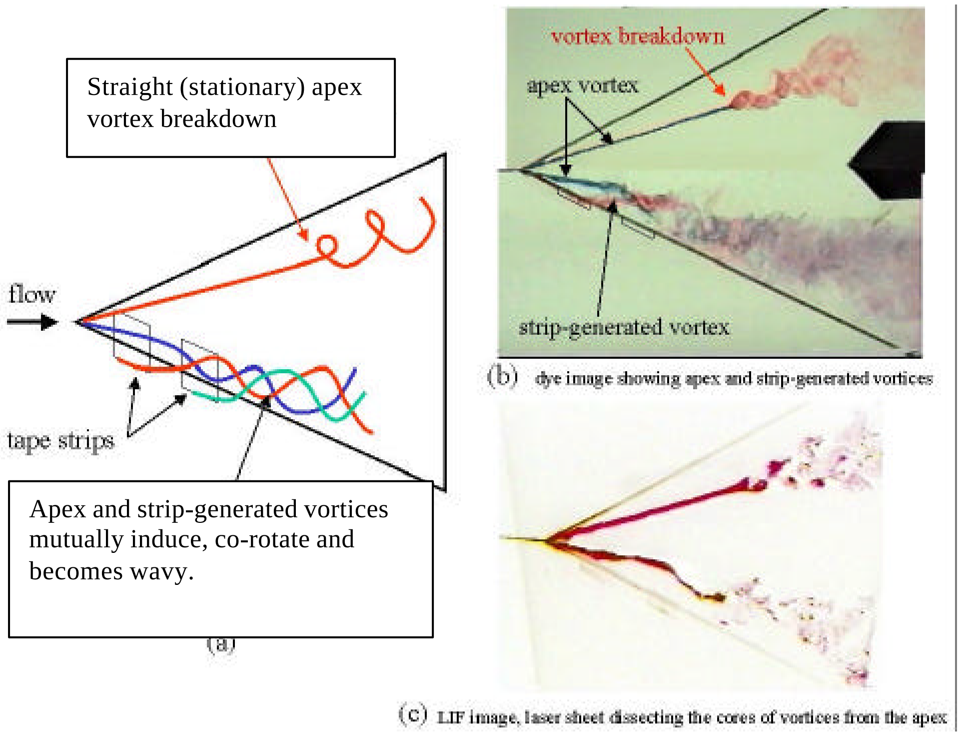


Fig. 8: Attaching the strip to the wing will introduce additional vortex. The system of apex and strip-generated vortices will induce each other, and change their path from straight to wavy (stationary to non-stationary).

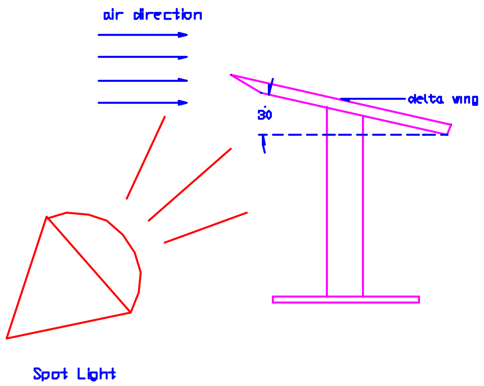
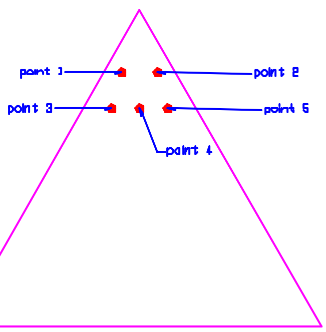


Fig. 9: Experimental set-up, showing the case when the heat lamp is used as the heat source (Heat gun is also used.)



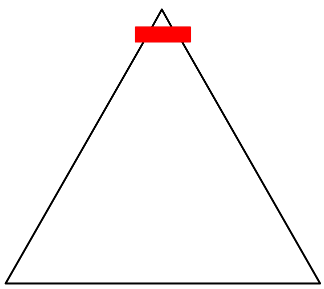


Fig. 10 (left): The distribution of measuring points
Fig. 11 (right): The big fin (strip) as a vortex generator

Table 1: Original experimental data

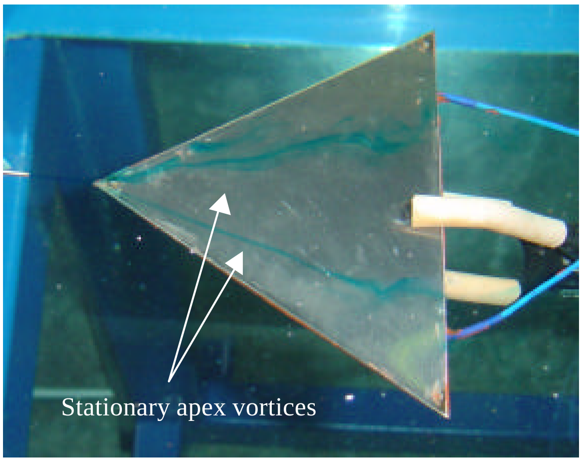
Set up	Heat lamp as heat source		Heat gun as heat source	
	CASE A: Stationary vortex	CASE B: Non-Stationary vortex	CASE A: Stationary vortex	CASE B: Non-Stationary vortex
Point 1	35.9	36.2	37.7	38.3
Point 2	35.9	36.2	37.8	38.3
Point 3	36.1	36.1	37.9	38.1
Point 4	35.9	36.0	37.8	38.2
Point 5	35.8	36.2	37.8	38.2

Table 2: Analytic data of *heat lamp* experiment

CASE A: Stationary vortex	CASE B: Non-Stationary vortex
$T_{average} = 35.92\,°C$	$T_{average} = 36.14\,°C$
$q_A^{"} = h_A(35.92 - T_{ref})$	$q_B^{"} = h_B(36.14 - T_{ref})$

Table 3: Analytic data of *heat gun* experiment

CASE A: Stationary vortex	CASE B: Non-Stationary vortex
$T_{average} = 37.8$	$T_{average} = 38.22$
$q_A^{"} = h_1(37.8 - T_{\infty})$	$q_B^{"} = h_2(38.22 - T_{\infty})$



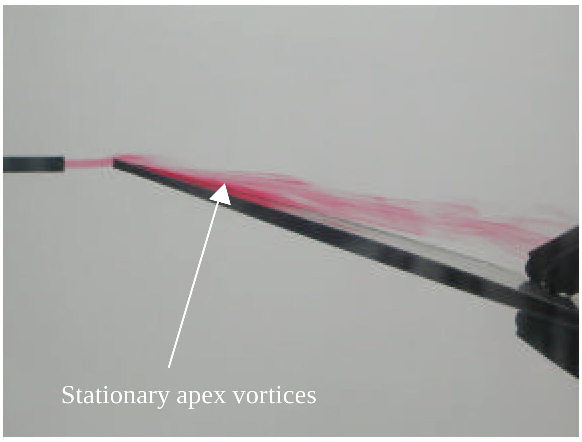
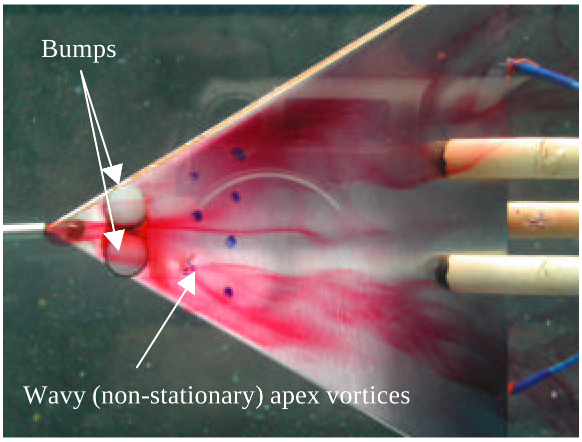


Fig. 12 (left): Delta wing model tested in water tunnel (top view). Blue dye shows the stationary apex vortices.
Fig. 13 (right): Delta wing model tested in water tunnel (side view). Red dye shows the stationary apex vortices.



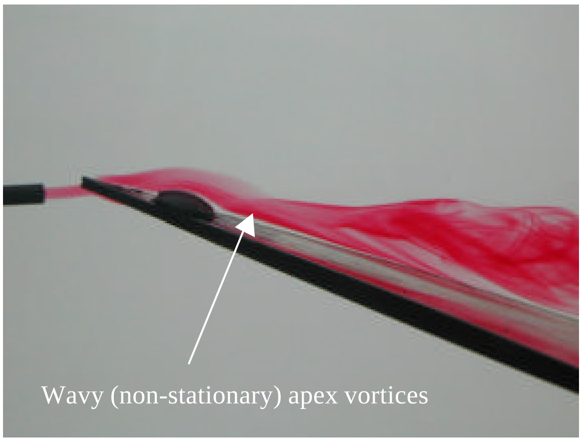


Fig. 14 (left): Delta wing model with two bumps (top view). Red dye shows the wavy (non-stationary) apex vortices.
Fig. 15 (right): Delta wing model with two bumps (side view). Red dye shows the wavy (non-stationary) vortices.

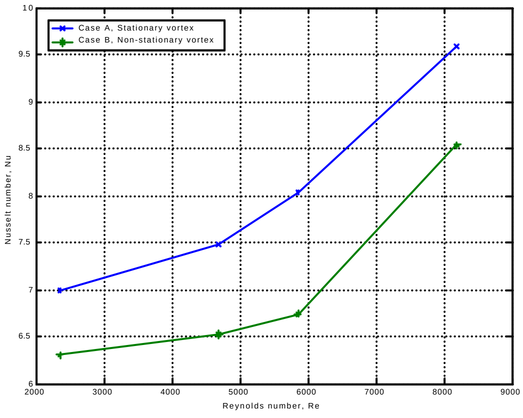
Table 4: Measured experimental data from water tunnel testing

Angle of attack (deg)	Freestream velocity (m/s)	Reynolds number, *Re*	Wing surface temperature (°C)		Temperature difference (°C)	
			Case A	Case B	Case A	Case B
20	0.02	2341.498	49.8	52.4	23.3	25.9
	0.04	4682.996	48.3	51.5	21.8	25
	0.05	5853.745	46.8	50.7	20.3	24.2
	0.07	8195.242	43.5	45.6	17	19.1
30	0.02	2341.498	49.6	51.9	23.1	25.4
	0.04	4682.996	48.6	50.6	22.1	24.1
	0.05	5853.745	47.6	49	21.1	22.5
	0.07	8195.242	45.3	48.1	18.8	21.6

Note: The freestream water temperature was 26.5°C.

Table 5: Calculated data from water tunnel testing

Angle of attack (deg)	Freestream velocity (m/s)	Reynolds number, *Re*	Convective heat transfer coefficient, *h* (W/m^2-K)		Nusselt number, *Nu*	
			Case A	Case B	Case A	Case B
20	0.02	2341.498	41.3008388	37.15481	7.001809	6.298925
	0.04	4682.996	44.1426396	38.49238	7.483585	6.525686
	0.05	5853.745	47.404411	39.76486	8.036559	6.741411
	0.07	8195.242	56.6064437	50.3827	9.596597	8.541474
30	0.02	2341.498	41.6584218	37.8862	7.062431	6.42292
	0.04	4682.996	43.5434182	39.92986	7.381998	6.769384
	0.05	5853.745	45.6070873	42.76931	7.731856	7.250762
	0.07	8195.242	51.1866778	44.55137	8.677774	7.552878



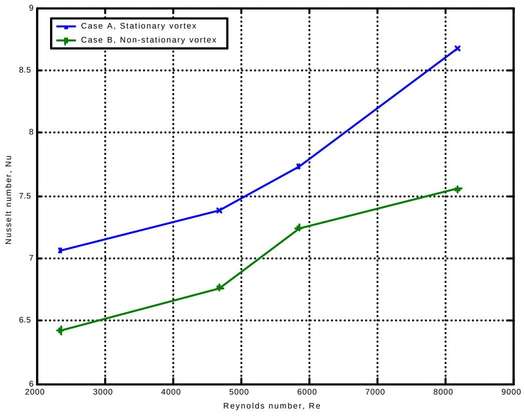


Fig. 16 (left): Plots of Reynolds number v.s. Nusselt number for both cases, at 20 degrees angles of attack.
Fig. 17 (right): Plots of Reynolds number v.s. Nusselt number for both cases, at 30 degrees angles of attack.