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6. AUTHORS John I. Galea Steven A. Orszag K. R. Sreenivasan	
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In this work, we report CFD studies of possible unsteadiness (flow transition and turbulence) effects in the injector/nozzle geometry of the Phillips Laboratory RotoCOIL (Chemical Oxygen Iodine Laser) Device. Earlier numerical studies based on the MINT code assumed steady, laminar device flow as a necessary compromise for the complicated reacting flow COIL problem. Other studies based on the GASP code involve similar assumptions. Also, other studies to date assume the so-called 'unit cell' approximation. The unit cell approximation is the assumption that the flow in the COIL geometry is periodic with period equal to the distance between small (downstream-located) iodicne injectors and half the period between the large (upstream-located) I injectors. Our work examines the validity of this assumption and estimates its effect on the flow. Relaxation of the unit cell will be, we believe, important in future work.

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John I. Galea, Steven A. Orszag, and
K. R. Sreenivasan

Departments of Mechanical Engineering
and Mathematics
Yale University
New Haven, CT

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John I. Galea*, Steven A. Orszag †, and K. R. Sreenivasan‡

Departments of Mechanical Engineering and Mathematics
P. O. Box 208283
Yale University
New Haven, CT 06511-8283

1. Introduction

In this work, we report CFD studies of possible flow unsteadiness (flow transition and turbulence) effects in the injector/nozzle geometry of the Phillips Laboratory RotoCOIL (Chemical Oxygen Iodine Laser) Device. Earlier numerical studies based on the MINT code (from Scientific Research Associates) assumed steady, laminar device flow as a necessary compromise for the complicated reacting flow COIL problem. Other studies based on the GASP code involve similar assumptions. Also, other studies to date assume the so-called 'unit cell' approximation. The unit cell approximation is the assumption that the flow in the COIL geometry (see Fig. 1) is periodic with period equal to the distance between small (downstream-located) iodine injectors and half the period between the large (upstream-located) I injectors.

In this study we examined the possibility of that COIL flows exhibit time dependence either through transitional or turbulent phenomena. We have also used indirect means to test the validity of the unit cell approximation. Our studies have included both two-dimensional and full three-dimensional simulations using the geometry and grid plotted in Fig. 1. Among the results of these studies we find that the unit cell approximation may be the cause of significant error and yield spurious simulation results for COIL. The basis for this conclusion is described below.

There are several cases to consider including cold and reacting flows and flows at various Reynolds numbers. In cold flows, the channel Reynolds numbers in the region near the injectors and upstream of the expansion in the COIL apparatus are moderate and perhaps suggestive of possible transition. However, our three-dimensional computer runs using laminar initial conditions showed decay of disturbances both with and without iodine injection through the two sets of injector nozzles in COIL. At first glance this suggests that these flows are not transitional but there is a flaw in this reasoning. As shown by our secondary instability theory of flow transition[1], the early-onset secondary instability modes that drive transition in channel (and other confined) flows require spanwise extent of order ten times that of the channel height. However, in COIL the unit cell dimension in the spanwise direction is roughly 1/10 the channel height. That is, the unit cell approximation, which imposes periodic boundary conditions, requires periodicity over a distance that is approximately a hundred times smaller than that required for secondary instability growth. In this case, the imposition of the unit cell approximation over such a small distance (typically the unit cell is 0.1cm in a channel

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* Graduate student, Department of Mechanical Engineering.

† Professor of Mathematics and Chair, Applied Mathematics. Member, AIAA

‡ H. W. Cheel Professor of Mechanical Engineering.

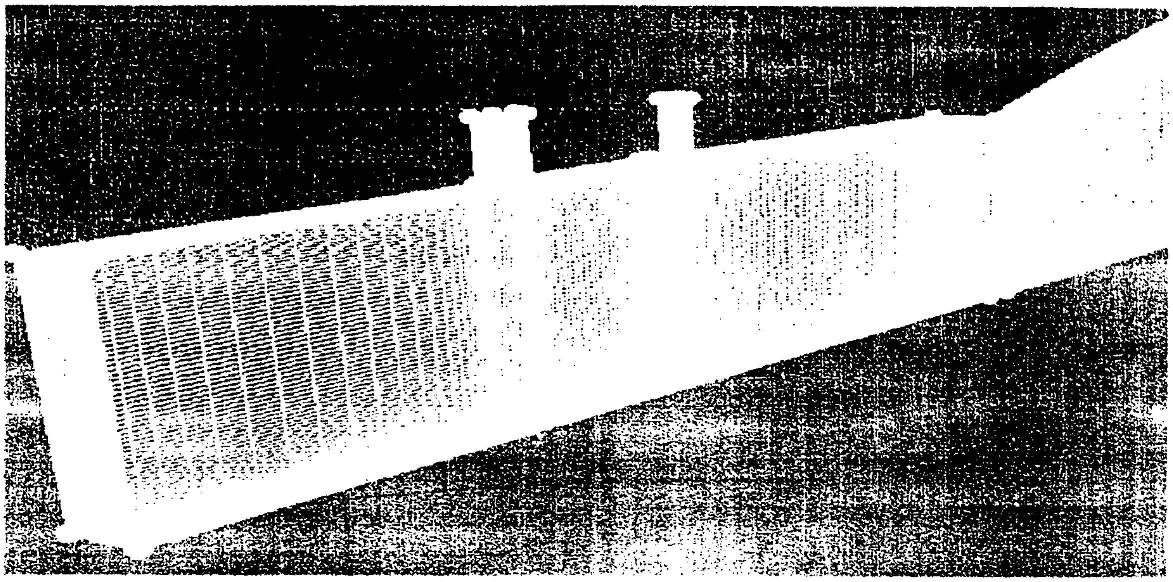

Fig. 1 3D COIL Geometry and Grid (courtesy of T. Madsen): a unit cell is plotted with the injectors in the upstream region (channel region) and expansion regions of the apparatus shown.

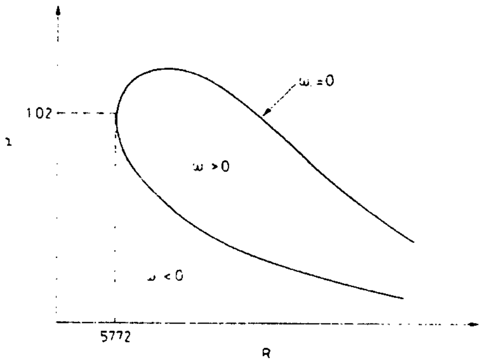

Fig.2 . Linear stability diagram for plane Poiseuille flow in a channel. Here $2\pi/\alpha$ is the streamwise periodicity length of the linear disturbance (normalized in units of the half-height H of the channel) and R is the Reynolds number based on center-line velocity U and H. ω_i is the growth rate of the disturbance normalized by U/H

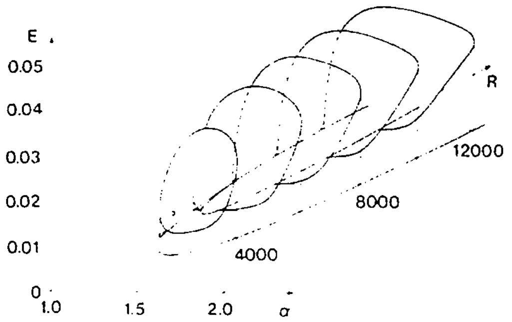

Fig. 3. Finite amplitude two-dimensional states of plane Poiseuille flow. The notation is as in Fig. 2 with the E the energy of the difference between the 2D state and the base channel flow. These states exist for R > 2980 and a limited range of streamwise periodicity lengths

whose height is slightly smaller than 1cm) strongly dissipates any possible instability motions in the spanwise direction. This can be easily seen by noting that with the unit cell approximation the lowest wave number in the spanwise direction is approximately 100 (in units of inverse channel height) so that the dissipative term in the Navier-Stokes equations is enhanced by a factor of $100^2 = 10^4$ This argument suggests that, as a minimum, transitional flow studies in COIL require relaxing the unit cell approximation by a factor 10 or more so that the minimum spanwise extent is at least 10 unit cells. A numerical simulation in such a geometry would require computation times several orders of magnitude larger than current simulations and would have memory storage requirements also that are significantly larger than currently used Both these requirements make it unlikely that systematic studies of transition would be cost-effective

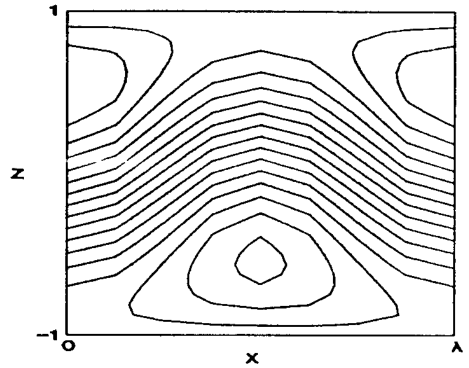

Fig. 4. Streamlines of the 2D finite amplitude state at R=4000 and streamwise periodicity length 2π/1.25.

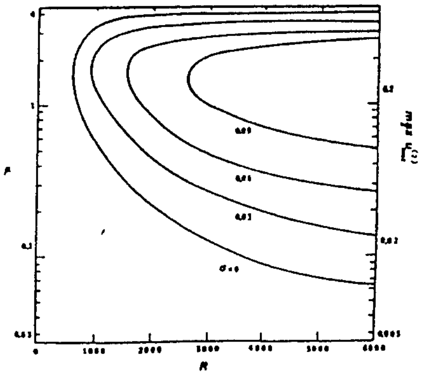

Fig. 5. Contours of constant growth rate σ for 3D secondary instabilities as a function of R and m, the amplitude of the 2D finite-amplitude state. Here σ is normalized by U/H.

2. Transition to Turbulence

The fundamental theory of secondary instability in wall-bounded shear flows (see Ref. 1) shows that two-dimensional finite-amplitude waves result from the classical linear (two-dimensional) instabilities of viscous shear flows (as described by the classical Orr-Sommerfeld eigenvalue problem). Classical instability theory shows that plane Poiseuille flow is unstable at Reynolds numbers larger than 5772[2] (see Fig. 1). The 2D evolution of these instabilities is not chaotic, leading to 2D stable finite amplitude states, which exist down to Reynolds numbers of roughly 2980 (see Figs.2 and 3) – at still lower Reynolds numbers these steady states do not exist, but decay very slowly in time even down to R of order 1000 . However, while these finite-amplitude states are stable to 2D disturbances, they are unstable to 3D perturbations, a 'secondary instability' at Reynolds numbers down to roughly 1000 – at R below 2980, perturbations are applied to 'frozen' 2D states in which the slow decay of the 2D finite amplitude motions is disregarded.

The most rapidly growing of the secondary instabilities at typical Reynolds numbers has spanwise periodicity roughly comparable to its streamwise periodicity. If the spanwise periodicity is enforced at a much shorter length scale, as with the unit cell approximation, significant dissipation takes place since the growth rate is corrected by viscous dissipation through an extra term of the form $-\beta^2/R$, where β is the spanwise wavenumber. In the COIL apparatus, the unit cell is so small that this viscous correction effectively kills the secondary instability.

The 'RADICL' cold flow in COIL (test name 9257cf11 with helium flow everywhere) is at 260°K and atmospheric pressure so the dynamic viscosity is 1.8 10^{-5}kg/ms and the Reynolds number based on channel half channel height is 1365. In reacting flows, the Reynolds number involved in COIL is somewhat larger than in the cold flows (typically larger by a factor of 2-3). Indeed, a simple calculation of viscosity for a mixture of 75% helium and 25% oxygen leads to a kinematic viscosity half that of helium, and thus twice the Reynolds number. At these Reynolds numbers, extreme care would be needed to avoid transition, while simulation of transition should avoid the unit cell approximation as discussed above. Time dependent transitional effects will be even more pronounced in the adverse pressure gradients of the expansion regions of the COIL apparatus.

3. Turbulent Flow in COIL

Since typical Reynolds numbers of reacting COIL flows are expected to be in the range 3000-4000 or more in the channel flow regions upstream of the expansion, these flows are probably turbulent in COIL. Indeed, even for cold flows, the flow in the adverse pressure gradient channel expansion downstream (that includes the lasing region) is turbulent, especially near the walls. While at may seem that the simulation of turbulent flows would be more difficult than the transitional case this is not necessarily true. With turbulent flows, the requirements on the three-dimensional geometry resolution may be significantly relaxed. For example, while transition studies require spanwise extent of order 10 or more unit cells, this need not be so with turbulence. There are three types of turbulent simulations to consider, namely turbulent simulation using DNS, LES, and VLES[3,4] methods. With direct numerical simulation (DNS) and large eddy simulation (LES), stochastic simulations of the flow equations and their modifications (for LES) are done. In order for these simulations to be valid, significant three-dimensional structures must be calculated. In other words, a two-dimensional simulation using DNS and/or LES would not give proper results. However, extensive experience over the past decade or so has shown that "thin" turbulence modeling (in which the spanwise extent is limited to a "thin" slice) can give reasonable simulations provided that the spanwise extent is large enough to accommodate the production of wall streaks and bursts. For the COIL apparatus this would require a spanwise extent of 1/3-1/4 of the channel height or, in other words, roughly 2-3 unit cells whether or not the injector nozzles are included in the model. While such calculations would increase the computational requirements by a substantial factor over those involved when the unit cell approximation was imposed, these calculations are still much smaller than for transition (see above).

The situation with respect to the unit cell approximation is improved if turbulent flow simulations are done using very large eddy simulation (VLES) techniques. In VLES only the largest scale, non-universal, eddies outside of the inertial range are simulated directly. All smaller eddies are treated *via* statistical theory which in our initial development of VLES was accomplished using renormalization group techniques. In this case, if there were no injection nozzles, it would be feasible to calculate the COIL flow in two dimensions. Indeed, we have performed two-dimensional VLES simulations of COIL geometry flows in which the injector nozzles are removed and in which the injectors are replaced by two-dimensional slot injectors. These simulations show the persistence of turbulence in the flow and its growth in the adverse pressure gradient expansion regions. Three-dimensional flow simulations using VLES have also been done and show the persistence of turbulence in the channel flow region and its strong growth in the expansion region. In addition, these three-dimensional VLES simulations suggest periodic shedding in COIL at a Strouhal number that translates into a frequency of about 50Hz in the COIL experimental apparatus. However, the latter result has not yet been demonstrated conclusively and requires much additional computational study.

The turbulence level is especially large in the unfavorable pressure gradient region accompanying the channel expansion (which includes the region lasing activity). At a Reynolds number of 4000, not atypical of reacting flow conditions, turbulence levels in this region are such that fluctuating velocities are in excess of 20% of the streamwise velocity. Some typical results for the turbulence intensity ($v_{rms}^2/2$), turbulence dissipation and velocity profiles are shown in Figures 6-14. Notice that, in the wall region of the unfavorable pressure gradient part of the flow, even larger turbulence levels are found.

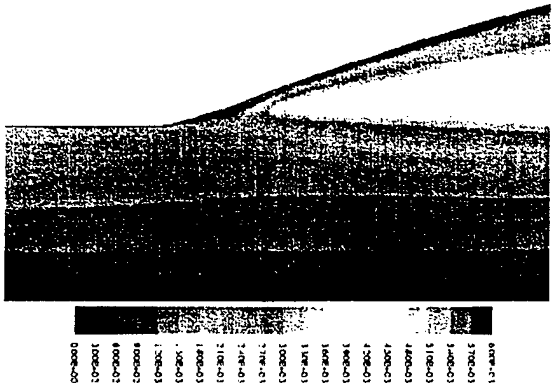

Fig. 6. Turbulent kinetic-energy (R=4000) on a slice between the injector ports.

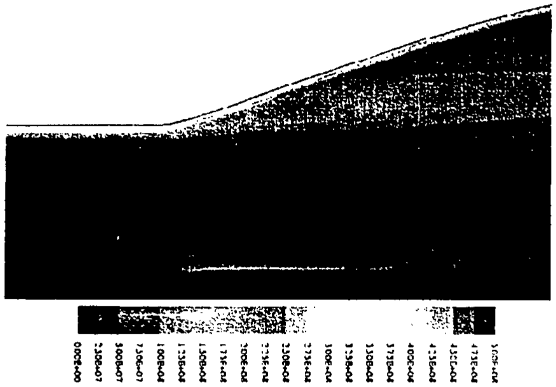

Fig. 7. Turbulence dissipation (R=4000) on a slice between the injector ports.

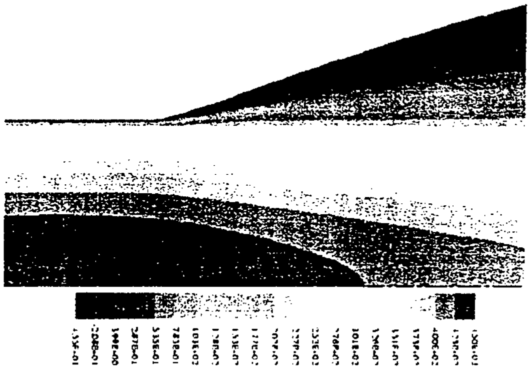

Fig. 8. Streamwise velocity contours (R=4000) on a slice between the injector ports.

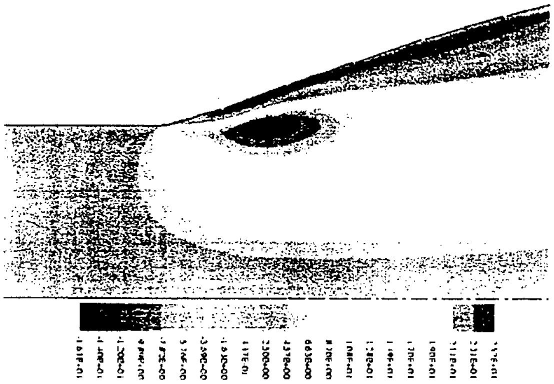

Fig. 9. Normal velocity contours (R=4000) on a slice between the injector ports.

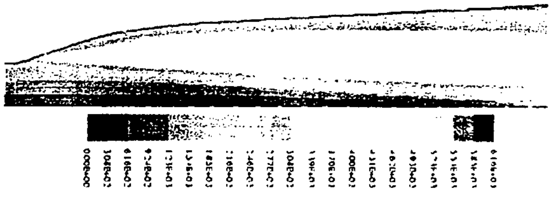

Fig. 10. Same as Fig. 6 but including the lasing region

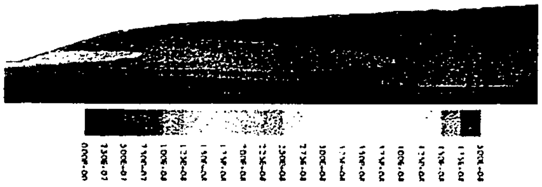

Fig. 11. Same as Fig. 7 but including the lasing region

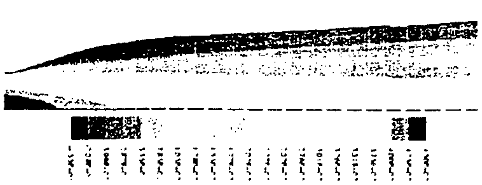

Fig. 12. Same as Fig. 8 but including the lasing region

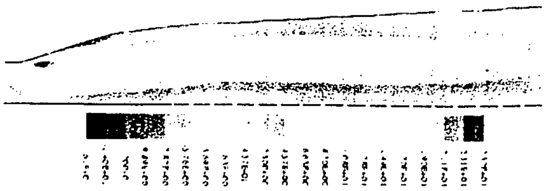

Fig. 13. Same as Fig. 9 but including the lasing region

The flow simulations are performed using a finite volume code with the two-equation VLES turbulence model on the 3D grid shown in Fig. 1. The inflow parameters are:

Mean velocity	375m/s
Pressure	7230Pa
Temperature	265°K
Density	$1.31\ 10^{-2}$kg/m3
Dynamic viscosity	$6.141\ 10^{-6}$kg/ms
Kinematic viscosity	$4.688\ 10^{-4}\mathrm{m}^2/\mathrm{s}$
Half-channel height	$5\ 10^{-3}$ m
Re (half channel height)	4000

A typical time step is 10-7 s and a typical grid uses 108 cells along the 16.5 cm flow region with 32 cells across the 0.1 cm unit cell and 32 cells in the normal direction (0.5 cm at inlet and 1.5 cm at outlet).

In Fig. 14, we plot the time variation of the v-velocity at a point near the throat at the beginning of the expansion (adverse pressure gradient region). The time dependence of the velocity seems to be persistent, but this requires further investigation.

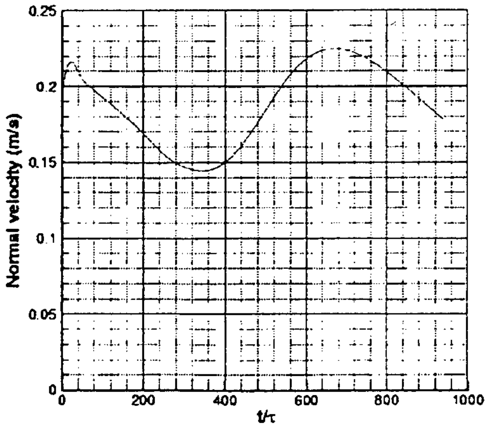

Fig. 14. Time dependence of the normal (v-) velocity at a point near the beginning of the adverse pressure gradient region.

4. Conclusions

Our studies to date show that both time dependence and turbulence are likely to be significant features of COIL flows, especially under reacting flow conditions. For cold flows, the question of transitional effects is a difficult one that like requires giving up the unit cell approximation. On the other hand, the unit cell approximation, while likely not to be valid for turbulent flows, is less severe for turbulence – it seems that cells just 2-4 times larger than a unti cell should suffice for DNS, LES, and VLES studies. The VLES results reported here show the presence of strong turbulence both in the lasing region and, especially, near walls.

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