To leave the thread of all time
and let it make a dark line
in hopes that I can still find
the way back to the moment
I took the turn and turned to
begin a new beginning
still looking for the answer
I cannot find the finish
it's either this or that way
it's one way or the other
it should be one direction
it could be one reflection
the turn I have just taken
the turn that I was making
I might be just beginning
I might be near the end.

(***Anywhere is***, ***Enya***)

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Abstract

In recent years the increasing livestock production and the demands for better conditions for animals and farmers in indoor agricultural industry has made air quality an important issue just like the reduction of (cold) downdraft, the reduction of pollutants etc. Pigs are mainly produced in stables with mechanical ventilation, and a relatively large number of pigs per unit area. Therefore an increase in lung diseases has been reported over the last ten years. So it is crucial to keep and obtain an air quality at a satisfactory level both for the animals and the farmers.

For many years the only way to consider and build different ventilation systems were through experiments and by using a basic tool of turbulence theory - the dimensional analysis which includes a lot of empirical work.

But for the last twenty years the development of the Computational Fluid Dynamics (CFD) area has made it possible to simulate the flow and to get a better understanding of the flow situations that occur. Only in recent years the expansion to three-dimensional models has made the results more accurate due to the increasing computational power, and the development of the theory of turbulence and the numerical methods behind.

But this has also introduced new problems like handling complex three-dimensional flows, separation, buoyancy etc. In many flows especially those featuring massive separation due either to blockage, or unsteadiness traditional turbulence modelling fails to represent the transport and energy cascade process in a credible manner.

The flow inside livestock buildings can be described as time-dependent and transitional; both isothermal and non-isothermal situations occur. A great part of the flow is governed by large scale structures. One new problem within the area is the boundary condition. The question is then how these complex geometries could be treated ?

But because the flow is often time-dependent and unstable, the use of statistical turbulence models like the k-ϵ method often has some shortcomings. Although the use of the Reynolds Stress Models (RSM) resolves some of the problems of the k-ϵ model like separated flows, turbulence-driven secondary motions, curvature and irrotational strains, the use of a time-averaging procedure is inappropriate for some transitional, separated or unsteady flows. An example is the flow passing a square cylinder where the oscillation in the wake is a problem because the 'mean flow' is not steady.

Due to the constant development in turbulence modelling and computational power the assessment of the next step in the modelling hierarchy, which is the Large Eddy Simulation (LES) is an alternative. Since the Large Eddy Simulation method is not based on the Reynolds Averaged Navier-Stokes (RANS) equations, the loss of information due to the time-averaging process gives no problems. The LES approach explicitly solves the large scales of turbulence motion and apply a model for the small scales (scales below

the numerical grid). Therefore the turbulence scales that are not solved by the numerical grid, constitute the subgrid. It is important to note that the large energetic scales (eddies) of the flow are affected by the geometry/boundary of the problem. And hence the boundary conditions become more important. They are also characteristic of the type of flow responsible for most of the momentum and energy transport and they are deterministic. This is in contrast to the small scales which are more isotropic, random and responsible for most of the energy dissipation.

In this project different methods to perform numerical simulations of air flow in simplified ventilated enclosures have been applied and developed. It started with the use of the general purpose CFD software, ***CFX***, AEA Technologies, England and a research code, ***LESROOM***, developed by Mochida and Murakami, at University of Tokyo, and ended with the development of a fast special purpose code to perform detailed numerical simulation using the Large Eddy Simulation. Apart from the Large Eddy Simulation model including different subgrid scale models, some of the standard turbulence models have also been applied, like the standard k-ϵ model, the low-Reynolds number k-ϵ, the low-Reynolds number k-ω (The Wilcox model), the ReNormalised Group (RNG) k-ϵ and finally the Reynolds Stress models which are included in the ***CFX*** software.

This was done in order to compare the different turbulence models. However, another main task was to develop and test the feasibility using LES and assessing the computational costs of carrying out LES in ventilated enclosures. To ascertain the necessity for using more advanced turbulence models it has been important to study the performance of these models in basic airflows encountered in ventilated buildings. Therefore the research conducted here has been carried out for relatively simple building geometries and inlet configurations, since adding complex geometry and inlet devices would make it very difficult to identify whether the discrepancies between computations and measurements are due to the turbulence modelling, the numerical errors introduced or whether these are specific to the geometry of the building or the inlet.

The work done in this project has been related to a national research programme *Control of Air Movement in Livestock Buildings*, where joint research between the Department of Building Technology and Structural Engineering, University of Aalborg, The Royal Agricultural and Veterinarian University, Copenhagen and Research Centre Bygholm, Department of Agricultural Engineering, Danish Institute of Agricultural Sciences, Horsens, is currently conducted. In this programme many experiments have been performed in a full scale section of a livestock building. The data from a few of these experiments have been used for comparison with simulations done in this project.

This ph.d.-project began from close to scratch with the many problems of startup and the use of CFD; problems with a given budget, searching for and buying a workstation, CFD software and later to become acquainted with the ***CFX*** software. This would be very similar to a company starting to use computational fluid dynamics.

The geometrical models simulated in this project have mainly been simulated under isothermal conditions. The flow patterns studied are mainly related to ventilation problems due to mixing types, and the results show that the two-equation type turbulence modelling still has problems when predicting mean air velocities and turbulence quantities. Especially the penetration depth of the air jet is over-predicted. Generally the performance of the Reynolds Averaged Simulation with different turbulence models is similar for these simple geometries.

The use of Large Eddy Simulation which is relatively new in the area of building ventilation problems gave much more information about the instantaneous flow field, however the computational costs are still high. Furthermore using the Large Eddy Simulation method revealed the following problems:

The need for a fast numerical solver and better implementation in order to improve the computational performance and efficiency, and improved numerical discretization when large velocity gradients have to be captured in the simulation.

Last but not least the need for a good inlet boundary condition is very important. Especially when the flow is mainly driven by momentum or the inlet area is relatively large compared to room height. These kinds of room air flows, the level of turbulence production is very high in the area near the edge of the inflow jet where large values of velocity gradients, in particular vertical gradients of streamwise velocity components, exist. The turbulent production caused by this large velocity gradient has very strong effects on the turbulence level in the whole room air flow (the effects of turbulence production are usually more important than the effect of inflow turbulence). But the flow pattern near the inflow boundary may be much affected by inflow turbulence. Also the turbulence length scale is very important as well as turbulence intensities. The method for generating inflow turbulence with a prescribed length scale (spectrum shape) is one of the most challenging and unresolved issues in LES research. One way is to carry out a preliminary LES calculation and store the velocity fluctuations to use them as inflow boundary conditions for room air flow calculations. In that way coherent structures are preserved in the inlet velocity profile which is important for both fully turbulent and especially for transitional problems. This approach is not difficult, but rather expensive and requires an extra amount of computational effort and disk storage.

To capture transitional flow phenomena LES will need more structural information or better information of the length scale inside the flow and not just a velocity profile with a random generated velocity fluctuation superimposed. The underestimation of the turbulent intensity could be attributed to the lack of coherent structures in the inlet boundary profile. But as long as only first order statistics e.g. velocity profiles are wanted, the point is less important.

When it comes to applying different models for the subgrid scale motion the following observation was made. The use of the Smagorinsky model captured the instantaneous and mean flow field satisfactorily, but the dependency on the Smagorinsky constant was large. But the need for special wall treatment in order to account for the reduction of subgrid scale lengths near the solid walls making this methods unfavourable, although it is simple to implement and very fast to compute. The dynamic model on the other hand gave results in good agreement with measurements. But the original dynamic model also needed a special treatment depending on whether the flow has one or more homogeneous direction(s) in which the equations could be averaged. For fully inhomogeneous flows only an averaging procedure in time is applicable. To overcome the need for special treatment, the mixed scale model and a dynamic one-equation subgrid model were also tested. The mixed scale model which was only tested by implementing it in the ***CFX*** software gave better results that the Smagorinsky model, but was not compatible with the dynamic subgrid models. The overall performance of the dynamic one-equation subgrid model did give better results than the other subgrid models, but were relatively expensive in terms of the computational costs, due to the fact that one more equation for the kinetic energy had to be solved, although the original dynamic model requires some spatial averaging to obtain numerical stability.

Also the need for a convective outlet boundary condition for the streamwise component of the velocity was illustrated in order to avoid unphysical oscellations.

Finally, it should be remembered that LES gives much more information about the flow field than the
RANS with one of the standard turbulence models. In view of this LES will not replace the traditional methods of turbulence modelling, but will be an improvement to the study of complex flow fields or transitional problems.

Keywords: Turbulent flow, Low-Reynolds number, turbulence modelling, ventilation enclosures, two-equations models, transition flow, isothermal flow, Large Eddy Simulation, Subgrid Scale Models, Boundary Conditions

The graphics in the following thesis have been created using many different software packages such as: Gnuplot, Matlab, Iris Explorer, Fieldview, and CorelDRAW.

Resume (in Danish)

I moderne staldanlæg stilles der store krav til ventilationsanlæggets funktion. Ud over at skulle fjerne varme- og fugt fra dyrene, skal ventilationsanlægget sikre en god luftkvalitet overalt i stalden uden at der herved opstå r problemer med træk. Disse problemer er fremkommet ved den kraftige effektivisering af husdyrproduktionen som landbruget har gennemgå et i de senere årtier. Dyrenes sundhed og forholdet mellem tilvæksten og foder forbruget er stærkt afhængige af klimaet i stalden og derfor også afgørende for produktkvaliteten og produktions-økonomien for den enkelte landmand. Desuden er der stigende problemer med sundhedtilstanden hos så vel dyrene som det personale der opholder sig i stalden. Dette har bidraget til at der er skabt interesse for luftkvaliteten i stalde.

Da de traditionelle beregningsmetoder til dimensionering af ventilationsanlæg ikke giver mulighed for at forudsige luftkvaliteten i lokale områder af stalden og kun i begrænset omfang tager hensyn til staldbygningernes geometriske udformning, vil en teoretisk model af luftstrømningen i stalderummet kunne anvendes til at give yderligere viden om luftstrømning og varmefordeling og dermed forekomsten af træk.

Luftstrømninger i et staldrum kan karakteriseres ved at de er instationære, ikke-isoterme, turbulente, domineret af storskalastrukturer og i visse områ der vekslende mellem turbulent og laminar strømning. Temperaturforskellen mellem den indblæste luft og staldrummet kan være op til 30 grader og dette vil sammen med varmeudviklingen fra dyrene have stor indvirkning på luftstrømningen. Endvidere vil randværdiproblemerne være komplexe, idet geometrien af en indblæsningsamatur og bygningsinventar langt fra er simpel at modellere.

Første fase af modelleringen er, med udgangspunkt i Navier-Stokes ligninger, at vælge et passende sæt partielle differentialligninger som model for luftstrømningen. Da de fulde Navier-Stokes ligninger beskriver et fluids bevægelse fuldstændigt under hensyntagen til alle forhold, lige fra indvirkningen af bygnings-geometrien på de store hvirvler i strømningen til dissipation of energien i de mindste hvirvler til varme vil det ikke være rentabelt at forsøge at modellere alle disse fysiske forhold. Denne form for modellering er kendt som direkte numerisk simulering og meget tidskrævende mht. beregningstid. Da Navier-Stokes ligninger består af et sæt partielle differentialligninger som skal transformeres over til et sæt diskrete ligninger ved anvendelse af et beregningsnet fordelt over beregningsdomænet, vil det derfor være nødvendigt at anvende et net som er for groft til at modellere de mindste hvirvler i strømningen. Derudover vil det derfor være nødvendigt at supplere Navier-Stokes ligninger med en form for turbulens- model, der kan beskrive hvad der foregår i strømningen som nettet ikke kan opløse og hvordan det indvirker på de større skalaer i strømningen. Endvidere skal der vælges randbetingelser der modellerer vægge, samt andre objekter i beregningsdomænet.

Ved numerisk simulering af en instationær turbulent strømning er det almindelig praksis at tidsmidle de styrende transport-ligninger (Navier-Stokes) og approximere de herved fremkommende korrelationer med en turbulensmodel. Eksempler herpå er to-ligningsmodellen k-ϵ , hvor to yderligere ligninger introduceres som beskriver bevægelsen af kinetisk energi og dissipation i strømningen, samt forskellige varianter af Reynolds-stress modellen.Men når strømningen er domineret af storskalastrukturer eller styret af instationære randbetingelser kan det være nødvendigt at benytte en anden løsningsstrategi, idet en tidsmidling kan give utilstrækkelig eller fejlagtig beskrivelse af strømningen. En lovende metode er Large Eddy Simulation (LES), hvor ideen er at dele det totale tidsafhængige strømningsfelt i et net- og undernet ("subgrid") bidrag til løsningen. Dvs. at de store hvirvler i strømningen opløses direkte i nettet og de mindste turbulente størrelser modelleres af en subgridmodel. Herved udnyttes at de største hvirvler, der er af samme størrelsesorden som staldgeometrien, er stærkt anisotrope og at de mindste hvirvler er isotrope. I de senere år er der sket en betydelig udvikling af disse subgrid modeller,- nemlig fra den traditionelle Smagorinsky (1963) subgrid model, til de dynamiske subgrid modeller efter Germano (1991), Lilly (1992), Zang (1993) og Ghosal (1995).

I dette projekt er hovedvægten lagt på implementering og anvendelse af modeller for LES, med de dertil hørende subgridmodeller, Smagorinsky, Dynamisk og 1-lignings Dynamisk modeller. I første omgang er det kommercielle strømnings simuleringsprogram **CFX** (fra AEA) blevet benyttet ved implementeringen af undernetmodeller vha. en bruger interface til programmet. Derved er det muligt at benytte **CFX** til at lave LES. Dog har det vist sig forholdsvis hurtigt, at anvendelse af **CFX** og LES modellen var meget tidskrævende selvom mindre end 100.000 netpunkter blev benyttet ved diskretiseringen af beregningsdomænet. En beregningstid på 14 til 30 dages uafbrudt simulering var ikke ualmindelig på en arbejdsstation. Dette var med til at vanskeliggøre undersøgelsen af flere forskellige staldrumstyper. Andre studier har ligeledes vist, at **CFX** ikke var specielt meget hurtigere på en supercomputer hos UNI-C, Lyngby.

Derfor blev forskningsprogrammet, **LESROOM** testet. **LESROOM** blev udviklet Murakami og Mochida, Tokyo Universitet. Programmet var skrevet i Fortran 77 og efter en grundig optimering var det muligt at anvende programmet på Cray supercomputer hos UNI-C med en god ydelse. Hvilket ville sige omkring 25 gange hurtigere end **CFX** på ovennævnte arbejdsstationen. Dog havde programmet en del begrænsninger, mht. nettype, undernetmodeller til LES, samt numeriske metoder. Derudover var programmet udokumenteret.

Herefter blev der udviklet et selvstændigt program, ***Solve4LES***, som bå de kunne håndtere de i projektet staldrumsgeometrier, samt benytte LES med flere forskellige undernetmodeller, og endvidere give en god ydelse på arbejdsstationer, samt tillade brug af forskellige metoder til løsning af den tidslige diskretisering og de forskellige hastighedskomposanter. Både en explicit og implicit metode blev implementeret og testet. Programmet blev testet og valideret på forskellige simple geometrier, som strømning omkring en firkantet cylinder og strømning omkring en kube i en kanal.

Under anvendelse af ***Solve4LES*** blev tre forskellige rumgeometrier undersøgt, Annex 20, hvor strømningen er fuldt turbulent. En backfacing step geometri (Restivo rum), hvor forskellige strømningsfaser med transitionelt (omslag fra laminar til turbulent) og fuldt turbulent strømning blev undersøgt. Endelig blev fuldskala SJVF-rummet i luftfysiske laboratorium på Forskningscenter Bygholm, Danmarks Jordbrugs-Forskning undersøgt under anvendelse af LES modellen og forskellige undernetmodeller.

Brugen af LES inden for simulering af luftstrømninger i bygninger er relativt ny og giver meget mere information om strømningsfeltet. Dog viser resultaterne fra dette projekt at LES kan anvendes på arbejdsstationer og PC'er, selvom LES stadigvæk er tidskrævende. Endvidere viste de dynamiske undernetmodeller sig at give gode resultater og kunne give information om strømninger der er ved at udvikle sig til turbulente strømninger. Netop dette område har det ikke været muligt at simulere med traditionelle turbulensmodeller så som k-ϵ model. Smagorinsky undernetmodellen hvilken er den ældste af alle disse modeller til LES, kunne ligeledes fange de instationære strømninger, men der var stadig en relativt stor afhængighed til den såkaldte Smagorinsky konstant. Denne metode var dog simpel at implementere og ligeledes hurtig til beregning i forhold til de dynamiske undernetmodeller. De beregnede tidsmidlede hastighedsprofiler for de forskellige dynamiske undernetmodeller viste kun små forskelle og var Smagorinsky og Mixed-Scale modellen overlegen. Ved sammenligning af Reynolds spændinger var Davidson (1997)'s dynamiske 1-lignings undernetmodel bedre end de andre.

Endvidere har brugen af Large Eddy Simulation vist følgende krav/problemer i anvendelsen: behov for en hurtig og effektiv numerisk løser, samt bedre implementering og optimering for at kunne reducere de store krav til beregningskapacitet. Ligeledes har bedre beskrivelse af randbetingelserne, specielt indløbs-betingelserne, vist sig at være af stor betydning; specielt for problemer hvor strømningen er under omslag fra laminar til turbulent eller hvor strømningen ikke er fuldt udviklet.

Endelig har det vist sig, at den PC-arbejdsstation, som programmet ***Solve4LES*** er benyttet på er pt. et år efter den nyeste processor teknologi. Og med den nyeste processor standard ville det være muligt umiddelbart at reducere beregningstiden med næste en faktor 2, alene ved anvendelsen af nyeste processor generation. Og forholdet til nyeste nuværende processor generation for UNIX-baseret arbejdsstationer, som f.eks. Alpha processoren, 21264@750MHz ville der være næsten en faktor 4 til forskel. Dette ville kunne reduceres yderligere med anvendelsen af parallel computer systemer.

Nøgleord:

Turbulent strømning, Lav-Reynolds tal, turbulensmodellering, ventilation problemer, to-lignings turbulencemodeller, transitionel/omslags strømning, isotermiske strømning,
Large Eddy Simulation, subgrid skala modeller, randbetingelser

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Nomenclature

Roman symbol

u', v', w'	velocity fluctuations in x-, y-, and z-directions, respectively
U, V, W	mean velocity component in the x-, y-, and z-directions (Reynolds Averaged components)
u_i	velocity component i the x_i-directions (tensor notation)
u, v, w	velocity components in the x-, y- and z-directions, respectively
u_τ	frictions velocity
p'	pressure fluctuations
p	pressure
Pr	Molecular Prandtl number
Q	Air flow rate
q	heat flux
Re	Reynolds number
Ra	Rayleigh number
Θ	temperature
Θ'	temperature fluctuations
Ar	Archimedes number
f_d	damping functions for wall bounded flow
k	kinetic energy
x_i	Cartesian space coordinates
G	filter function

Greek Letters

α	thermal diffusivity
β	thermal expansion coefficient
Δ	width of grid filter
$\tilde{\Delta}$	width of test filter
ΔT	temperature difference
δ_{ij}	Kronecker delta
ϵ	dissipation rate of kinetic energy k
	von kármán constant
μ	dynamic molecular viscosity

μ_t	turbulent (or subgrid scale) viscosity
ν	kinematic viscosity = μ/ρ
ν_t	turbulent (or subgrid scale) kinematic viscosity = μ_t/ρ
ρ	density of fluid
ω	specific dissipation rate of kinetic energy k
	stresses

Subscripts

i,*j*,*k*	indices in x, y, z -directions
0	reference value
detach	point of detachment in the flow
re-attach	point of reattachment after the flow has detached.
in	inlet
out	outlet
R	Reattachment length
rms	root-mean-square
s	step hight
sep	separation length
sgs	Subgrid scale
w	wall

Superscripts

$(\ )'$	fluctuating quantities
$(\ )''$	resolved turbulent fluctuating quantities
$(\bar{\ })$	bared quantities are filter variables on the grid level
$(\widetilde{\ })$	tilde quantities are filter variables on the test filter level

Other symbols

$\langle\ \rangle_T$	averaging over time
$\langle\ \rangle_{xyz}$	averaging over all space dimensions.
$\langle\ \rangle_z$	averaging in the spanwise direction.

Abbreviations

AMG	Algebraic MultiGrid
BLAS	Basic Linear Algebra Subroutine
BLASSM	Basic Linear Algebra Subroutine for Sparse Matrices

CFD	Computational Fluid Dynamics
CG	Conjugate Gradient
DNS	Direct Numerical Simulation
GMG	Geometrical Multigrid
GMRES	General Minimal RESIdual method
HSMAC	Highly Simplified Marker and Cell method for velocity-pressure correction
IAQ	Indoor Air Quality
IC	Incomplete Choleski
ILU	Incomplete LU
ILUT	Incomplete LU with threshold
LES	Large Eddy Simulation
MAC	Marker and Cell method for velocity-pressure correction
MG	Multigrid
MPI	Message Parsing Interface
MRILU	Matrix Renumbering Incomplete LU
MSIP	Modified Strongly Implicit Procedure
NOW	Network Of Workstations.
PISO	Pressure Implicit with Splitting of Operators
PPE	Pressure Poisson Equation
PVM	Parallel Virtual Machine
RANS	Reynolds Averaged Navier-Stokes
RAS	Reynolds Averaged Simulation
RCM	Reverse Cuthill-Mckee ordering
rms	*root-mean-square*
RSM	Reynolds Stress Model
SGS	SubGrid Scale
SIMPLE	Semi-implicit Method for Pressure-Linked Equations
SIMPLEC	SIMPLE-Consistent
SIP	Strongly Implicit Procedure
SMAC	Simplified Marker and Cell method for velocity-pressure correction