Chalmers University of Technology
Gothenburg, Sweden

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The *Nordic Wind Tunnel*

proposal to build a very large turbulence research facility

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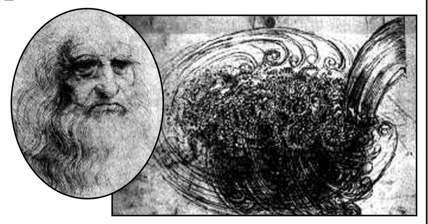
The problem...



Leonardo's observation of turbulent flow: Drawing of a free water jet issuing from a square hole into a pool (courtesy of eFluids.com).

Turbulence has been studied for a long time, but is nevertheless often cited as the *last unsolved problem in classical mechanics*.

Many classical ideas of turbulence theory date back to the 1930s and 40s. These ideas have evolved since, but it has never been possible to truly test most of them because of the absence of *large and long enough, high quality* (low background turbulence) research facilities.

"Turbulence remains one of the most outstanding research problems facing the international engineering, physics and mathematics research communities"
Charles R. Doering, *Professor of Mathematics, The University of Michigan, USA.*

"The proposal by Professors George and Karlsson is quite a timely one, given the number of significant turbulence research issues that remain unsolved."
Professor **Robert A. Antonia**, *ARC Senior Research Fellow, The University of Newcastle, Australia.*

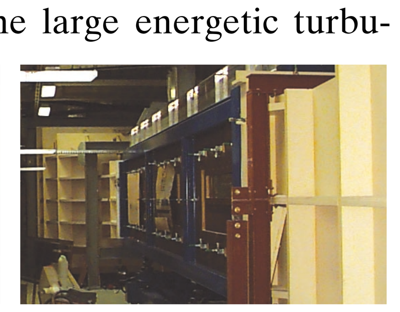
Experimental work in a large research wind tunnel is needed to solve a number of fundamental questions and enable scientists and engineers to further improve computations of turbulent flow. Simply put, the problem is how to achieve a separation of length scales, energetic to dissipation, of 10^5 or larger – and still be able to resolve the smallest scales occurring in the flow with the smallest technically feasible probes (approximately 10 µm).

"The most important question is whether or not the vast store of information and knowledge that has been obtained at low Reynolds numbers for a variety of important classes of turbulent flows is applicable to the high Reynolds numbers that are characteristic of most real engineering flows. In order to investigate this question, a wind tunnel capable of reaching these high Reynolds numbers while permitting instrument resolution typical of experiments at much lower Reynolds numbers must be available. This is just what the Nordic Wind Tunnel is designed for."
Professor **James M. Wallace**, *Univ. of Maryland, USA.*

Wind Tunnels

Existing research wind tunnels are too small to reach high enough *Reynolds numbers* while still permitting *resolved measurements* of the smallest scales. They are either too short for the turbulence to evolve from its upstream (initial) conditions, too narrow for the large energetic turbulence scales to be free from the influence of the walls, or have too high a background disturbance (free-stream turbulence) level to extract the features of primary interest.

Example 1: BLWT 2, Univ. of Western Ontario: Good overall size, insufficient flow quality (designed as wind engineering facility).



Example 2: MTL wind tunnel, KTH, Sweden: Good flow quality, insufficient size (limited by available building).

Are there alternatives?

Despite increases in computational power and progress in numerical techniques, it is currently not possible to resolve the small scales at high Reynolds number. Even with computational power doubling every 18 months, it would take several decades before a model-free, direct numerical simulation (DNS) of the simplest flow case of non-decaying isotropic turbulence could be performed with the separation of scales 10^5 equivalent to the wind tunnel proposed here (resolution requirements for a comparable simulation: number of grid points > 10^{15}).

"Despite the impressive developments in Computational Fluid Dynamics over recent decades, [...] many of the fundamental questions still facing the turbulence community cannot possibly be answered in the foreseeable future without recourse to laboratory work."
"There are now a number of relatively small-scale facilities designed to allow study of very high Reynolds number flows (*via* use of very high pressures, exotic gases, or whatever) but these are all inherently limited by the technical difficulties in developing and applying appropriate instrumentation. In my view, there is much to be said for the only possible alternative approach: going to much larger scales, so that existing, well-developed techniques can be used. Your proposal is therefore very exciting and, if I may say so, very well thought out."
Ian P. Castro, *Professor of Fluid Dynamics, University of Southampton, UK.*

What makes the *Nordic Wind Tunnel* unique?

The *Nordic Wind Tunnel* overcomes the shortcomings of present research facilities and is proposed for construction at Chalmers University of Technology. It would be

- wide enough to remove the effect of side walls on the energetic turbulence scales
- fast enough and large enough to get the necessary high Reynolds numbers, yet still resolve the dissipative scales
- long enough and with low enough background disturbances to obtain the necessary downstream development times and will thus provide an experimental facility capable of resolving some of the oldest questions in turbulence while also testing conclusively new ideas.

In the unique *inverse design process* it was asked what length and time scales needed to be resolved to conduct "meaningful" measurements (e.g., resolution of wall layer to obtain shear stress) and what Reynolds numbers needed to be achieved in the experiments to be performed (e.g., boundary layers, far wake, decay of isotropic turbulence) to help resolve fundamental questions and sort competing theories. These length and time scales and Reynolds number criteria depend on the flow being measured. The size (length and cross-sectional area of the test section) and performance (maximum free stream velocity) of the proposed wind tunnel facility were then determined by what can be resolved with existing probes.

The small scales of the flow become smaller with increasing flow speed or pressure. To quote the late *Professor* **Tony Perry**, *University of Melbourne*, who realized the dilemma and stated that: "Big and slow - is the way to go".

"It is our view that the facility [...] would be second-to-none as an experimental research tool for basic turbulence research into high Reynolds number incompressible flows. This is particularly true for the range of scales of turbulence resolved."
Poul Scheel Larsen, *Professor of Fluid Mechanics and* **Knud Erik Meyer**, *Associate Professor of Experimental Fluid Mechanics, both at Denmark Technical University.*

Example of one design criterion:

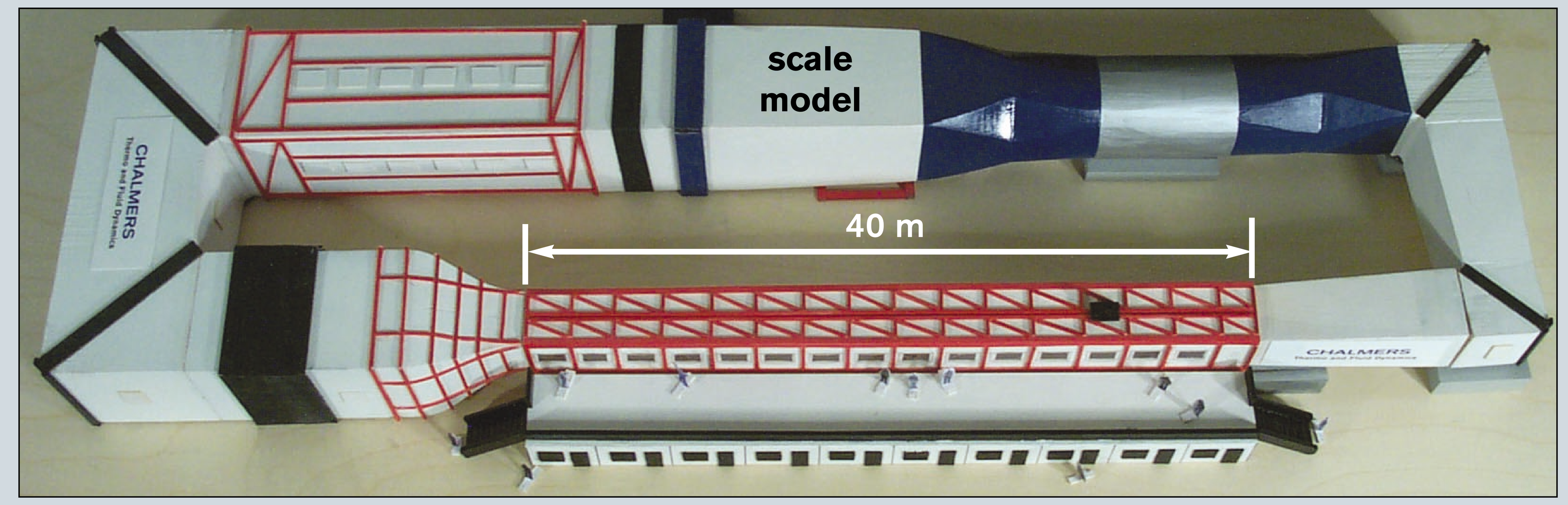
For wall-bounded turbulent flows the requirement was that one viscous length scale can still be resolved (using a micro-LDA or a micro-PIV system, with a measuring volume height of 10 µm) while achieving a Reynolds number based on momentum thickness of at least 100,000.

Other "base case flows", e.g. decaying turbulence or wake flows, also provided further size and flow quality criteria.

Result of the inverse design/dimensioning process:

A wind tunnel with a
- **test section of 40 m length**,
- cross section after contraction **3x3m**,
- maximum **free stream speed 40 m/s** and a
- **free stream turbulence u'/U of < 0.02%**.

The total dimensions of the facility are: length: **79 m**, width: **21 m**, height **7 m**.



The ***Nordic Wind Tunnel...***

...will be a very large (test section: length 40m, cross-section 3m x 3m), low-speed wind tunnel with very low background turbulence (u'/U < 0.02%). It will be the only facility in the world with this combination of size (length *and* width) and high flow quality.

...will enable turbulence experiments on a scale that will not be achievable with computers for many decades. It will be used to address many of the fundamental questions that have held back turbulence research for half a century.

...also has tremendous potential for commercialization due to its unique size and flow quality. This ensures its long-term viability serving a variety of industries.

...will be operated as a major Nordic and European Facility. Many of the world's leading scientists have enthusiastically endorsed this facility (see letters of support) and they expect high quality work to result from it.

***Nordic Wind tunnel* scale model**

Some problems that can be addressed in the *Nordic Wind Tunnel*

The Nordic Wind Tunnel will enable experiments specifically designed to answer fundamental questions in turbulence.

"[...] coherent structure identification in turbulent flows, a crucial aspect for drag reduction, noise, vibration, mixing etc."
Professor **J. P. Bonnet**, *University of Poiters and Centre National de la Recherche Scientifique (CNRS), France.*

"[...] this well designed wind tunnel will allow to focus the studies in several directions, spanning from isotropic to inhomogeneous flows."
Professor **Paolo Orlandi**, *University of Rome "La Sapienza", Italy.*

"The current controversies over the law of the wall and the law of the wake imply an uncertainty about boundary-layer behavior at high Reynolds number - which should worry designers of aircraft, ships and other high-*Re* artifacts. My view is that "theoretical" arguments are unlikely to settle the matter so that high-*Re* experiments are needed"
Professor **Peter Bradshaw**, *Flow Physics and Computation, Stanford University, USA*

"[...] we seek answers to large eddy and direct numerical simulation results that can only come from experiments performed in an exquisite facility of the type proposed. We expect the data will enable us to critically assess validation issues."
Professor **Andrew Pollard**, *Director of Computational and Experimental Fluid Dynamics Laboratory, Queens University, Canada.*

"[...] the facility seems suitable for investigation of a turbulent boundary layer at high Reynolds numbers, when its thickness reaches tens of centimetres as, for example, on a plane fuselage in real flight"
Victor V. Kozlov, *Professor of Experimental Fluid Mechanics, Siberian Branch of Russian Academy of Sciences, Russia.*

"A limited deep understanding of turbulence impacts the design of many devices ranging from aircraft and aircraft engines to the cooling of micro-circuits. There has been little fundamental progress in the last 20 years, in part due to a serious lack of experimental data which your tunnel would provide. I can therefore offer my wholehearted support for your project as I believe it will be an important contributor to solving the turbulence problem at the international level."
Professor **P. Hutchinson,** *FREng, Cranfield University, UK.*

Viability as engineering facility

The *Nordic Wind Tunnel* will be designed as a facility for turbulence research, but has tremendous potential for commercialization due to its unique size and flow quality. This ensures its long-term viability as engineering facility serving a variety of industries.

"I am also convinced that industry in Sweden and abroad will find such unique facilities indispensable for development and advancement of many technologies, to mention especially aviation, space research, road-, rail- and water vehicles, as well as for studies of atmosphere and ocean dynamics. Last, but not least, such facilities will add much to the already enviable international prestige of Chalmers University of Technology and Sweden as a whole."
Professor **Kemo Hanjalic**, *Head of Thermo-Fluids Section, Delft University of Technology, The Netherlands.*

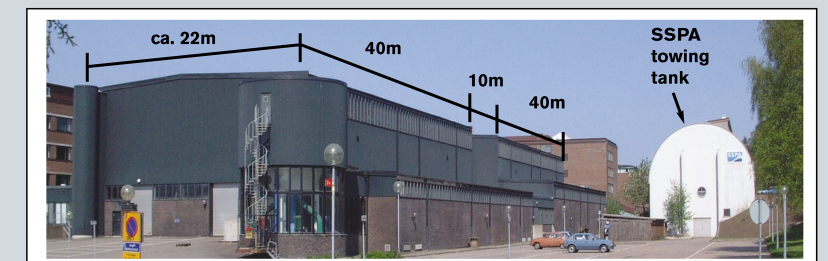
"Perhaps we have learned nearly all we can from research done in small wind tunnels. The proposed *Nordic Wind Tunnel* will allow research to be conducted at higher Reynolds numbers with fewer wall effects. This will give us greater insight into turbulence and its control"
Professor **David E. Stock**, *Washington State University, USA.*

"These [fundamental physical questions] should not be confused with the atmospheric, wind engineering and sporting commercial applications which are also a possibility.."
John L. Lumley, Carrier Professor of Engineering, *Cornell University, USA.*

Location

The *Nordic Wind Tunnel* will be built at Chalmers University of Technology, a major technical university located in Gothenburg, Sweden.

The *Nordic Wind Tunnel* will be housed in an existing, available building, adjacent to SSPA. Finding this building was a coincidence, it happened *after* the basic design/dimensioning process. Surprisingly, the two laboratory halls (pictured above) combined can actually house the *Nordic Wind Tunnel* in its current configuration!



Available laboratory buildings on Chalmers campus.

The *scientific infrastructure* at Chalmers is already in place with both W.K. George and R.I. Karlsson joining the faculty at Thermo and Fluid Dynamics, and the moves of their respective laboratories to form the new Turbulence Research Laboratory (TRL) at Chalmers.

"The team at Chalmers is very strong, the project is timely and clearly stated. It could well become a major resource for Europe, the US and other countries – a CERN for turbulence."
Zellman Warhaft, *Professor of Mechanical and Aerospace Engineering, Cornell University, USA.*

Cost estimate for construction

The cost of construction has been estimated at **6 million Euro**. The estimated engineering design cost is one tenth of the total cost, **0.6 million Euro**.

The engineering design phase will end with a *bidding conference*, at which the facility – in parts or whole – can be bid on by contractors.

Timetable:
- design: 1 year
- construction: 1-2 years

"I admire the careful thought which has gone into this facility design, which when built will surely put Sweden in a leading position in wind tunnel research. I also admire the great ingenuity in picking a design for building this facility at a very modest total cost."
Professor **Russell J. Donnelly**, Director of Cryogenic Helium Turbulence Laboratory, *University of Oregon, USA.*

International Cooperation

The *Nordic Wind Tunnel* will be made available for researchers from all over the world. Leading international scientists are looking forward to using it in their research.

"I welcome this proposal, not just because it will provide a proper modern experimental facility in Europe, but because it will also provide a focus for collaboration from all sides of the European turbulence community."
Professor **J. D. Gibbon**, *Imperial College, London, UK.*

"I can envisage this wind tunnel becoming a strong catalyst of European research in turbulence and Chalmers becoming an important center for turbulence research as a result."
J. C. Vassilicos, *Imperial College, London, UK.*

"With our own research facilities, we cannot achieve the high Reynolds number flows we would like to investigate and we therefore hope to collaborate with you on boundary layer research at high Reynolds numbers. We are also interested in flow around obstacles and we would like to carry out this experimental work at low blockage ratios. Your planned wind tunnel will permit this kind of research."
Dr.Dr.h.c. **Franz Durst**, *Professor of Fluid Mechanics, University of Erlangen, Germany.*

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for more information on the ***Nordic Wind Tunnel*** visit
http://www.tfd.chalmers.se/trl/windtunnel/

or e-mail:
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William K. George **wkgeorge@tfd.chalmers.se**

Overview of a selection of wind tunnels:

organization	Johns Hopkins	Colorado State	U.W.Ontario	IIT	KTH	ASU	Chalmers
location	Baltimore, MD	Ft. Collins, CO	London, ONT	Chicago, IL	Stockholm	Tempe, AZ	Gothenburg
tunnel name	Corrsin tunnel	MWT	BLWT2	NDF	MTL	UWT	Nordic WT
operational in	1950s	1963	1984	1994	1991	1987	(proposed)
contraction ratio	25:1	9:1	4:1	6:1	9:1	5.5:1	5.4:1
test section							
TS length L [m]	10.00	29.30	38.25	12.19	7.00	7.40	40.00
TS width W [m]	1.30	1.80	3.40	1.52	1.20		3.00
TS height H [m]	1.00	1.80	2.50	1.22	0.80		3.00
test section Umax	32 m/s	36 m/s	30 m/s	120 m/s	69 m/s	36 m/s	40 m/s
turb.level u'/U(%)	0.1	> 0.1	> 0.1	< 0.03	< 0.02	0.01	< 0.02
	("typical tunnel")	(long and large test section)		(low free-stream turbulence)			