GIAN Lecture 1:

Introduction of the Course and

History of

Rarefied & Microscale Gasdynamics (RMG)

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Good morning!

This is great honor to have this kind of course.

I used to attend professional courses arranged by AIAA in past decade.

So I'd like to learn.

At this time I'd like to share what I learned on this particular subject.

Next seven days, with respected colleagues, I'd like to share the recent development in the area of RMG and viscoelastic fluids.

When I sit here, just it occurs to me, rarefied, micro, viscoelasticity, are three different subjects.

In this room, did you watch the movie Kung Fu Panda?

Any of you? How many? Oh a lot, that is good.

In that movie, the words, still I can remember exact words. That word is like

Yesterday is mystery, oh, history

Tomorrow is mystery, and today is present.

Can you follow? So in that context, I guess rarefied is yesterday, micro is today, viscoelasticity is tomorrow, at least to me, it is to me.

Rarefied gas is old subject, micro and nano is current subject, and why in the world I bring viscoelasticity?

Some of you have never heard of it, but I recently became interested in this subject, to me it's future, to me it is mystery.

I will explain why all those three things can be touched within unified, unifying yesterday, today, and tomorrow.

So that is the main point in at least 15 my lectures.

Keep that in mind, what I am thinking. That is exactly I want to share with you.

For others, you can find everything in my papers or others.

I asked prof. Rakesh, close this one.

So he will distribute my about 12 or something papers on this subject, and also old papers I found very useful.

I struggled with those papers.

Some of those papers probably the most famous one would be this one, 1949, written by Prof. Grad.

This is classic.

Even though gas kinetic theory began with Maxwell, Boltzmann, this Grad's work is a serious attempt to use otherwise very theoretical gas kinetic theory.

I don't know how many of you try to read this one, because, I don't know, exact page numbers, more than hundred pages, it is like book, a lot of mathematics.

They will intimidate, I guess, you. So Probably one or two trials of this paper, probably you give up. Rather than reading this masterpiece, probably you will learn from textbook.

So I will show you sometimes that is a bit dangerous, because you can miss original thought of Grad, because textbook is always next generation's summarizing what they think that Grad thinks.

That is different. So I recommend you, I will distribute, including this one, to all of you.

Probably, this afternoon, if you have laptop, bring it. You can try to read it on your screen when I touch that kind of subject.

I was given 75 mins, and then I will focus on lecture one.

This is another opening.

Lecture 1 is the brief introduction of course and history of RMG, rarefied, and micro gas dynamics.

I guess this is the laser point.

Oh, so, rarefied means low-density state, either high altitude or artificially maintained on ground, some vacuum industry so on.

Microscale, small scale, micro or nano, you can sense that typical size is, you just pick up, one piece of your hair, that is hundred micron.

You divide ten times, that becomes ten micron, which is thickness of shock wave. Supersonic aircraft, there is oblique shock, that thickness is that small.

We are talking about gas motion in that thin structure or small device.

Viscoelasticity, I think, in the science and engineering in general, concept is very very very important.

Visco is different from elastic.

This is a realm of continuum mechanics, because fluid and structure are combined.

In elementary mechanics, I think, all of you took solid mechanics, fluid mechanics.

Fluid mechanics is visco, solid mechanics is elasticity.

Probably you heard about Hooke's law and E, something like that.

Why, in the world, as trained as fluid dynamicist, I became interested in this stuff, because it is there, every day, polymer, shampoo, all those fluids, it is a kind, it includes also elastic effects.

So therefore it is big business, and also you can find such complex fluids, or we call it, soft matters, so in nature, a lot.

Complex fluids like macro molecular polymer, visco-fluidic elastic, amorphous solid.

In solid, there are several types; one would be metal, another one is, here, amorphous solid, another would be like wood, they are different solids.

I am talking about amorphous solid, so, like glass. Glass is very very famous subject, waiting for another Nobel prize in chemistry, or physics, very difficult to understand.

I am not that interested in glass, but I am, at least, interested in some elastic effects in fluid motion.

I will talk about this one, maybe last lecture, two lectures.

And then why I am interested in? Because, when I look at Boltzmann equation, I will talk about again again again.

Don't be confused by mathematics. Once you are intimidated by mathematics, you cannot think big.

Kinetic molecule and macroscopic continuum, to me, all kinetic theories and all others are the same thing.

Based on individual atomic motion, you want to understand big one. They are different.

Why continuum? Continuum word is slightly confusing. You should not say it is just continuum.

It is, basically, you can define statistical average or ensemble average. If you define such one, I call continuum.

It not necessarily should be continuum. That is big jump.

Barrier I see is two things; one is whether or not you can define statistical average. Or you can define 2nd law of thermodynamics. Those two I worry about, nothing else.

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All others I will not be intimidated by difficulty or limitation.

Then our goal here is to try to combine or at least describe fluid motion, including molecular level, thinking as one, from Boltzmann equation to conservation laws.

I will avoid using Navier-Stokes laws, because, when you say Navier-Stokes, it's limited.

But conservation laws are fundamental physical laws. Many people misunderstand, it's because ordinary fluid dynamic textbook not teaching that way.

You just immediately introduce Navier-Stokes equations and then ask students memorize.

That killed fluid dynamics, (made it) not interesting, too difficult. Because, you show Navier-Stokes equations for the first time, it is messy equation.

I deliberately avoid that kind of thing. Conservation laws, macroscopic continuum means conservation laws.

Kinetic molecule is, as name indicates, trying to describe individual motion.

And then fundamental physics of RMG in the form of non-Navier, meaning overcoming limitations of Navier introduced in 1822, about two century ago, also Fourier, we call constitutive laws.

In fluid dynamics, it said inherent property of fluid, but that is questionable. Sometimes, those constitutive laws by definition may depend on flow condition, in particular, viscoelastic case.

There is some danger. Why? NS is obviously inherent flow quantity, not depending on flow. But that may not be true in general fluid. That kind of things I will discuss.

And boundary condition. Mathematicians normally hate boundary conditions. Once you have boundary condition, you cannot do anything. So you lose your job.

So in many cases, they work always without boundary condition. That is limitation. With that limitation, they can develop powerful mathematics, so you can use. That's all right.

But remember. In order to have practical outcome, you must provide boundary condition, which is very important, in particular, RMGs.

I will show why. And then I mention viscoelastic, solid mechanics, this is not fluid dynamics. When I talked about these things, Hookean.

Hookean law is solid mechanics E, so you provide strain and you measure stress, and then you plot it, you have beautiful curve, until there is some flattening. That was we call Hookean, that was almost four century ago.

But polymer, all those shampoos, they do not behave like this one. So I'd like to provide non-

Hookean molecular basis. Very few people have done that.

I try to do so. I am not sure I will be successful. But, based on what I learned from yesterday's rarefied, today's micro, I am looking forward to tomorrow's viscoelasticity.

By the way, when you ventured into new subject; there is good thing and also bad thing. Good thing is it keeps motivating you, you are exited.

But bad thing is yesterday and today you established some reputation in that field. If you venture into new subject, you are just beginner. No one will appreciate you.

You have to compete from the beginning, sometimes very difficult. So just remember that. Sometimes, as researcher, you need to do so.

You did a fabulous job in phd work. Later on, you will find you are running out of some new idea. Then you have to find your own new idea. But, be prepared, in that case, you are just beginner.

All right.

So, another one I'd like to emphasize is that all things in this 15 classes are a personal opinion. So research is in essence a personal journey in the sea of knowledge, this is how I define (research).

Be very careful about interpreting my way of thinking. Always try to add some your own word or thinking.

I was trained in aerodynamics, aerospace engineering. In master degree, I did, because it is around 87 or 89, at that time, CFD was hot topic, but my supervisor was not expert in that one, he requested me to do some experimental work, so I did aeroacoustics.

So I built some fan, and anechoic chamber, and measure sound level using microphone and spectral analyzer, based on fast Fourier transform.

And then I took some venture to the abroad study and then Michigan. Under supervisor Prof. Roe, he is a CFD expert. But, somehow, I ended up very different subject, magneto-hydrodynamics.

The reason is simple. Originally, Prof. Roe suggested me numerical scheme of Maxwell equation after two years course work and after qualified exam.

I spent 3 months and then develop 2D FVM Maxwell solver and explained Prof. Roe. And then next semester, I remember late September, I don't remember exact name, but someone from outside, he gave some seminar on MHD.

I was impressed by those, some issue. And then I asked Prof. Roe I want to change subject. I don't want to work on Maxwell equation as my phd topic. The reason was simple.

(After 3 month work) I realized that the Maxwell equation is linear equation mathematically. So I just can project what would be the final outcome after 2-3 years. I was probably developing 3D complicated numerical code for linear equation. Sometimes I did not like that. So I would rather have some challenging subject in fundamental level, so MHD seems fit for that category.

Why? Because, remember 93-94 early days of CFD application to MHD. And then that person Riemann shock tube problem, so gasdynamic shock problem, you have shock tube and the membrane, high pressure, and low pressure, and break this membrane, then I don't know which one is right, rarefied, shock something like that, always rarefaction waves and shock waves are separated.

But, in particular that seminar, I was impressed because in that MHD you have this kind of, so gasdynamics, which is more like very famous Sod problem, rarefaction and then contact discontinuity, and then shock wave, something like that, so in this gas, this propagating right direction, and then this low density and pressure rises up, and then this is density, contact discontinuity, rarefaction, anyway this kind of thing, always rarefaction, contact discontinuity, shock wave are separated, this region, as time goes on, this distance will be bigger.

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But in MHD I found there is interesting something like that. Shock and rarefaction are attached, we call, compound wave. But nobody knows why this is, why is this one. Numerically you can just apply finite volume method to 7 by 7 MHD 1D equations, so you can find such line. And then nobody explained why we have this. Because of that, it highlights nonlinearity. So I just immediately saw, I wanted to do these things, changing from linear Mawxell equation to nonlinear MHD.

Anyway, that was the change of subject. During the process, of course, I worked on CFD, but in order to understand these things, I spent most of time in mathematics library, because I sense that there must be something going on mathematically. So I thought I cannot find answer for this kind of problem from engineering literature, because they are too busy in CFD. So I spent two years, there are separate engineering school and mathematics library separated. At that time, there is no pdf, you have to visit library, you have to make copy all those papers on your own expense.

And then somehow I a little bit began to understand the core of problem. I think one year later I found an answer from very different mathematical journal. It is about oil recovery quadratic system.

Normally in gasdynamics, you are working on Burgers equation. And you have a viscosity term. You have here or mu. This is Burgers equation, this is scalar because unknown is just one. One day I found they call quadratic system. They look like, because more than two, we have u, v, derivative, and then important one is, in this case, this is quadratic because it is square, power of two, that is we call scalar quadratic, in MHD it turned out … I found this equation, and mathematicians never thought about MHD. They just, because they are mathematicians, naturally they thought this is scalar quadratic, then they think about 2 by 2 system. That is mathematicians superbly do this kind of thing. So I found this one then I applied all those theories to MHD, exactly the same system. That was applied math.

And then after phd, I became interested in RMG rarefied, microscale gases, and then because I was hired by university, not only I have to do fundamental work but also I have to bring the money. Also I have to train ms students and phd students in subject on these things. I like those two. I mean. The good thing about university is you can choose whatever you want to do. In my case, parallel, I do both, fundamental thing and very practical one. This is practical subject.

OK. Why I became interested in this RMG. The reason is, that 1994 intense study of phd, one of my colleague side by desk, name of Brown, his subject is kinetic theory and continuum equation. And then he developed some numerical methods for moment equation. And then somehow the final result is not that impressive. You have beautiful equation about two pages, I can show you when I have time. But the final conclusion is it is no better than Navier-Stokes. So that impressed me a lot.

Again it is like I like challenging topic at that moment. No anymore here right now. But in that young age, 29, 30 something, I was very ambitious, so that I kept that problem, one day I wil try to solve it. That was the beginning of rarefied microscale gas dynamics.

Anyway, it is a personal journey. So the same will be for you. You will have not only one topic but more more. So be prepared. Stay hungry and ambitious, at least, 30 something, until 40 something maybe not. You have to be careful about choosing your career and topic. But 30 something 20 something you have leverage to do and to try everything you want.

OK. Research goal. This is one I am trying to do.

This is the current topic. Fundamental idea intensive, and also application labor intensive. In particular this case, I am relying on students. But, in this case, I am keeping by myself sometimes on this topic, because it is all about idea, all about idea. I can do these things while in travel like this occasion, or on the mountain, I can think, because it is matter of idea. That case sometimes lucky enough, I can generate enough ideas to publish good journals including RMG, MHD.

In this area, I have to produce some practical output, like survivability, icing, lightning, generating aerodynamic data for weapon design, and so on. Recently the lunar plume-dust interaction, Korea tries to launch explorer maybe 2-3 years later to the moon, so that case rocket motor will land down, and then rocket motor will generate the gas. The gas impinges on surface of the lunar, we call, regolith, very special, because lunar is billion year old, and no atmosphere. That is different from what you find in the earth, very different, dust is very different.

Once those plume generates those dusts, pumping up, there is no air, no drag. It can gain speed Mach number 5, anyway, those dusts, within a couple of minutes, circling all over the moon. That is topic. The US has already done that. I am trying to do more efficiently. Maybe Rakesh be aware of this topic. … Oh, you are working on it, very good.

It is multi-phase, very interesting problem, it is more like aircraft icing. In icing, you have droplets, carried by air, but the present of droplets will not interfere air itself, that is one-way approximation. That approximation is working. The question is that kind of thing, mathematically very important. And challenging one.

OK. Why, in this course, as I said, I mean, yesterday, today, and tomorrow is unified. My idea is this one, as I said, bold proposition any material undergoing internal motion basically have two parts in molecular level, either move or do something or undergoing interaction I avoid collision

Gas dynamics interaction occurs through collision or near collision, but viscoelasticity case may not be that simple. In that case, just interaction would be enough some f close or particular moment, that macromolecule undergoes some interaction. That is all I need.

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Either move or interaction. Mathematically kinetic dissipation. Through dissipation those irreversible processes come in, very very important one. That is why we need thermodynamics here, because in fundamental level there is dissipation and that is collision. In those collisions you have to worry about 2nd law of thermodynamics.

In kinetics, no it is just moving without any interaction, movement interaction. Therefore either gas or liquid or even viscoelasticity can be unified within that concept. That is my proposition.

Then with that concept you can develop some mathematics. And then model and later you can try that model at practical calculations and try to describe/explain those complex fluid motion in more efficient way with some physics attached. That is what I am trying to do.

I already mentioned here. I will talk about more details in last page.

In this lecture, most of materials you received this morning, part I, I think 6 lecture notes, you will find many cases very simple problem. So why I carefully chose this topic? Because again concept, idea is more important than all details.

Once you are just intimidated by or confused by details, you cannot see big picture. So, like rarefied, micro, those challenging topics, you need clear understanding of what you are trying to do there. In order to do that, I limit topic very simple problem, in many cases, analytic, even I am training CFDers. I like CFD but I like theory more than CFD, because that can give me clear understanding. Sometimes in ideal level, clear understanding is more important than all those beautiful contours.

Also at the same time I was training engineers. I am supposed to build some airplane. With that mind always, even though I am working on theoretical subject, always I have in mind practical approach. If I find, oh this theory, while beautiful, there is a fundamental limitation in application, I probably will not pursuit it. So all the topics I chose is carefully chosen both, either fascinating in theory and also in application.

Then I already mention mesoscale. Mesoscale means micro molecular level. Macro is continuum, or statistical average is possible, between, I call mesoscale. Please remember this word, very important one. Whenever you try to understand soft matter, complex fluids, all those stuffs, mesoscale viewpoint is key, including dissipative particle method, something like that. It's all about mesoscale, even turbulence modelling. It's all about.

So, why things are so complicated, because you are trying to depart from safe ground defined by Navier-Stokes, linear laws. Most of engineering is based on linear law or first-order. This is what textbook taught you, Hooks law, NS law, Fourier law, all about this on. But RMG requires leaving from the safe ground. You have to explore unknown territory, which I call, second-order nonlinear.

By the way, I mean, mathematics is sometimes so complicated. But, (to) engineers, what is important is concept. So my favorite test problem to all graduate want-to-be is “can you distinguish ordinary differential equation and partial differential equation, and also what is difference between linear and nonlinearity?” That is two most important problems, I think, every engineers must know.

So ODE and PDE are simple. So I already mentioned, this is PDE, right? This is PDE. But you will know this is partial derivative, so you know this is PDE. In PDE, you have, what is it, independent variable is more than two. Definition is, if independent variable is more than two, that becomes PDE, because you have to distinguish t from x, otherwise you will use dx, because independent variable is just one. This is the first problem.

And then linear and nonlinearity. I told you my story. I wasn't impressed by linear Maxwell equation, but I was impressed by nonlinear MHD. That means I pretty much sure I understood linear and nonlinearity. This is simple, I mean, if you go back to middle high, probably you have function f x and then if you choose x 1 and x 2, instead of just 1, then whether they become x 1 and f 2. If this is valid, that is linear. If it is not true, that is nonlinear. It is that simple.

In nature, of course, all things are nonlinear. But if you are working on small deviation or small deformation or small velocity gradient, that is nonequilibrium. Otherwise, everything is homogeneous. All living animals are dead, there is wind motion, no fan rotating. Every disturbance will provide gradient.

When this is small, then nature can be explained by linear. But this is big, hypersonics, supersonics, temperature gradient is high for given time. Then nature cannot be explained by linear law. That is RMG about. That is first encounter, at least, in fluid dynamics. Please remember this simple thing.

Mathematically complete different story. Linear equations all can be solved by hand or by symbolic mathematical software. Nonlinear is not. Each case is very difficult. Each case requires some ingenuity to solve nonlinear equation, because nature is so complicated in general. So because of that, I prefer analytic solutions.

Also another one, by the way, mesoscale means, initially you have individual molecules, and then in top level you want to define statistical average. In order to do that, you need at least some number of molecules, how many, it will depend on problem, it can be thousands, it can be ten thousands, I don't know. But you have to carefully think about that.

My point is if I can define statistical average, then, from kinetic equation, I can develop those continuum equations, which will give us mesoscale connections in the form of viscosity, in the form of Hooks law, and so on. That is what I am trying to do here.

But difference is I start from kinetic equation. That is different. You can derive those equations from experimental, or heuristic or empirical approach. But subjects you are dealing with are so complicated, that method will not work. Case by case we can propose some good model to describe shampoo, but exact the same model cannot be used to, not shampoo, some milk, or other substances. That case we need kinetic theory. I will show you how to do it.

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Another point is always qualitative holistic over quantitative fragmental agreement. What I am saying fragmental means, for example, most of you, mechanical, or aerospace engineering, you have airplane, you have to worry about lift coefficients but also drag coefficient, too. Because lift coefficients, you have to be up in the air, and drag coefficient, you have to build airplane efficient.

But the exactly same CFD code like ANSYS FLUENT, you run one airfoil fluid case you check lift coefficient and drag coefficient together. And then provide this solution to your supervisor or customer. They will look at CL first. In many cases, satisfied, oh that's what I expected. In many cases, Cd, are sure this is data you are giving me? Many cases Cd is not accurate, which means even one set of solutions, whether or not you are looking at Cl or Cd, your confidence is different.

So that RMG, in particular, you can make your theory so good, while you applied that method to slight different output like Cd, you miserably fail. I want to avoid that. That is what I meant, rather than fragmental knowledge, I always holistic. I want to make sure that our theory is at least balanced in predicting something. In this class, also, I try to do so.

Also qualitative, not quantitative.

And also validation and verification. You must distinguish verification and validation. I will explain this one probably next lecture. Very important, in short, we call V&V, because ANSYS FLUENT sells a lot of licenses and a lot of money, because they are verified and, in many cases, validated.

So RMG, in particular, because very few experimental data, and the equations you are dealing with are so complicated, in many cases, very difficult to verify, but they are very important.

So, this one, above all, I said alien spirit is needed, because textbook probably you will not find answer to your question, so because, as I said, you are talking regimes beyond safe 1st order linear laws. We are talking second-order, at least, I am not talking about third-order. By the way, I went through conceptual revisions, because I started from this subject 1996 and 1997 very seriously, it is 20 years ago.

Even though I am based on Prof. Eu's generalized hydrodynamics, I could derive computational models, but my understanding of that equation change from the time. In many cases, that is typical one. Be prepared.

The things you think right now would be very different from tomorrow. With that difficulty, I will share that kind of things.

And also in particular, viscoelasticity, I never published that idea to open journal. One trial was rejected as normal. I am not that disappointed, because, during the process, those 20- years, papers I am most proud of normally rejected, because the thing I presented was serious one, it may threaten the competitors.

So be prepared this thing. I am preparing the same thing in the viscoelastic field. I also am beginner as I told you. I am not expert in that area. So anyway, I will share that kind of things.

Also, I mentioned failure and struggle. I will share some of review comments I got. That is necessary. Sometimes review process I got advised it became another journal paper, in my case, 2014 paper I am very proud, because I fought with anonymous those reviewers, one or two.

Above all, but nonetheless, I cannot convince it, even though in my heart I am confident, I cannot demonstrate, I cannot convince opponents, it took two years. And please not afraid of such things, very very important. And also try to show you hands-on theoretical derivation, it's simple, I am not talking about very complicated computer programming, it's simple Fortran programming, but I will show you the power of such thing.

So because most of you are phd candidates I heard become a next generation. Sometimes I like reading this kind of articles, typically physics today, or others. Because it gives me prospect and how I have to think my research, so on. In this case, I call alien spirit, so which means try to step outside the established line of reasoning including textbooks.

Sometimes, you have to deliberately choose this path. Another one is need to feel comfortable with being different. And textbooks will not help very much. I like this word, it's codified set of solved problems. I think textbook is defined this way, codified set of the solved problems, it is not unsolved problems. That is personal opinion of authors, even though they are influential and respected. Nonetheless that is their opinion, and that is importance of reading by yourself the original journal paper.

OK. Try to scrutinize everything we learned from textbooks, in particular, underlying assumptions. Because what happened was Prof. Grad published that beautiful piece of work in 1949, over the one hundred pages, but the next followers somehow skipped those vital assumptions. And that was forgotten. Then one generation later people do something very strange, because they didn't pay attention to those underlying assumptions. In many cases, that is typical. Always try to talk to the person who developed original theory. Do not rely on publication, because it was polished.

So again this is one thing I'd like to emphasize. Big guestions.

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What are the essences of RMG? To me, I told you, mesoscale is required. One needs to think beyond linear 1st-order world, that kind of thing. The bottom line is it is just movement and interaction. That kind of thing. To me that kind of thing is essence of RMG.

What is the ultimate origin of the Knudsen minimum? In every rarefied gas dynamics this is famous problem. I think some of you already knew that Knudsen minimum. Knudsen is the name of a physicist. Minimum is minimum in mass flow rate. We have a tube. Pressure-driven. One end is maintained high pressure, another one is low pressure. Then you can expect flow will come this way. And whether or not is rarefied state or dense state, rarefied in particular state, mass flow rate somehow increases after a critical Knudsen number. Very strange. That is we call Knudsen minimum. So many many publications. I like that problem. But I'd like to challenge this morning, what is ultimate origin behind this thing? You think you know the answer?

To me, no, I do not know. I will tell you why, what is bothering me. In phenomenological theory, it is simple. You can measure. You have model. You can make easily adding an extra slip. You can make always minimum. But that does not necessarily explain whole thing. Because you have only information of mass flow rate. My challenge is, how about temperature profile? So mass flow rate is just one quantity again.

Among many things, in particular, if that is integrated, there is a danger. Because, you integrate, once you integrate, a lot of details are lost. The final outcome looks ok, but what happens between (is not ok). No. That is challenge. Later on, I will give you some hint.

But that kind of things. So if you think those simple problems are already solved, no. It is not solved, in the sense of it. If you are satisfied with explaining Knudsen minimum, it is all right. If you are interested in holistic viewpoint, you have to still work.

OK, another big question.

This was ten years ago. There was a debate. I remember the name Herwig, Germany, probably from internet, you can find it. I guess, I am not sure, the last name is Gad-el-hak, something like that. This person, Herwig Germane researcher, about 10-15 years ago, when micro gas channel is hot. And this person said. I am not particularly against him, I never met him, I do not know him. But he represents some groups. Oh why you are bothered by the second law?

We have beautiful NS equations. And then, using ANSYS FLUENT, run it, it will explain what you find microchannel. That was their opinion. With some slips. On the other hand, including me and Gad-el-hak, oh, we need 2nd-order or something else. That kind of things. Right now, no more this group. Because, probably you are here to learn such things.

Nature is not that simple. Nature is complicated, we need to develop some complicated. Not afraid of complexity. If nature requires, you have to do it. So, anyway, it is not simple extrapolation. I will show you, later on.

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I am supposed to, 45 mins, 25 mins, OK.

This is again why V&V is difficult. Too many computational models. You can propose another slip, second-order, so on. You can publish it. Too many computational models, very few experimental data. Many cases, just mass flow rate. We do not have temperature profile. We do not have pressure, we only have stream-wise pressure distribution, we do not have cross-stream (distribution). They are difficult to measure. That is one problem.

DSMC, while beautiful theory, it has also limitations. So I will show you how to verify DSMC. I will explain also experiment data. EU micro gas network, they are spending some money in particular experiment work, like Professor Colin, Imperial College, I think they are doing fantastic work. So you can use it for V&V.

Sometimes, there is lack of theory, like a diatomic gas. I will show you my opinion. But, no general consensus. What kind of kinetic theory? Monatomic gas is Boltzmann equation. No question about it. Beyond that, there is no consensus.

Another big issue is boundary condition. As I told you, mathematicians hate it. But we have to live with it. There is solid wall boundary interaction. I don't think there is a fundamental theory enough to explain everything. We are still relying on some empirical, heuristic methods.

All my lectures are based on my publications. Most of publications are somehow authored by myself, it is single authored. The reason is simple, as I told you, it is idea intensive work. Not necessarily I do not need students. While I am supervising many students, this is subject I am still keeping. Therefore, I am pretty much sure what's going on all those papers.

MHD papers. Why bring these MHD paper? Because there is mathematical skills that can be useful to RMGs. That's important. In particular, dynamical system. Dynamical system is very well respected subject in mathematics. A couple of Fields medals coming from dynamical system. I learned in MHD to solve those nonlinearities. I learned a little about the dynamical system. And I found again again very very powerful. I will show such thing.

And then, RMG papers. Mostly are Physics of Fluids. I do not know how/why I started from PoF. The name is very good, because RMG is somehow Physics of Fluids. Journal of Fluid Mechanics is number one journal in fluid dynamics, but mechanics is something limited a little bit. Anyway, I started from my academic career from publishing PoF, and I am still doing so. I do not have good relationship with JFM. I do not know why. But I am very proud of community citizen in Physics of Fluids. I will often use PoF Physics of Fluids, JFM Journal of Fluid Mechanics, JCP Journal of Computational Physics, C&F Computers and Fluids, and so on. Most of lecture notes are based on these things.

Recently another two papers in Physics of Fluids. As I told you, viscoelastic fluid is an ongoing topic. Why I open this thing to you guys? Because research is not about individual effort. So I have no problem in sharing my idea to all of you. You can take it and, if you have skills, you can develop your own theory. I will share some of it with you. Oh, I once attended APS fluid dynamics meeting, and then presented this one.

I am supposed to take memo, because you have 20 mins.

00:57:11

I cannot do these works without my graduate students. Former postdocs. Dr. Xiao, he is a professor in the Northwestern Polytechnical University in Xian. Through him, I learned about all kind of Chinese activities in this area.

Dr. Rana, he is, I think, in the United Kingdom, he is postdoc, he is a former student of Prof. Henning Struchtrup. He did some MD work. And then, my graduate students, Iranian, Karchani, and so on, and some from India too, and some Korean.

OK. This is professor Kumar will distribute those papers. I will talk about Maxwell, and Grad. This is the most important one, on the kinetic theory of rarefied gases, in Communications on Pure and Applied Mathematics, leading journal in this subject. And then, 1952, the profile of a steady shock wave, I mean, you can sense that, why prof. Grad, very interesting to see checking his biography. I think, that is the end of world war II. I think he is a part-time student, not full-time student. It is not very famous school like MIT, I think it is New York Polytechnic university something like that, a part-time student. But his supervisor was a very famous person, Friedrich something like that. He found enormous talent in mathematics. He guided him to pursue phd. This is work of his phd study. Beautiful work. Can you imagine at that time there is no word processor? Writing all kind of mistakes. He is very skilled, I think, mathematician.

Then 1952 paper. Why he developed this one, because government, the state, wants to learn about shock wave, either bomb or hypersonic vehicle. Remember just before dawn of space age. He belongs to top mathematical group in that effort. That is why he chose that one. That is why he chose the first application of his theory to shock wave. But he miserably failed. You can sense his frustration. I will show you, maybe later on, I will show you his frustration.

Because of that, if you follow his kinetic theory, there is bright side, there is fanfare, there is success. But there is failure. Very few people remember his failure. That is normal human behavior. They always cite the first one, but skip second one. That will give you a failure. But, if you are serious about research, you should not be afraid of failure. You have to live with it.

So I am joking I learned something like this one. Best friend to any serious researchers must be the basket. Where is it? Oh there is. Because full of all kind of rejected papers. That should be your best friend. I completely agree with it. Research is not just every day's success. You struggle, you are disappointed, you are rejected. Overcoming you can have your original thought. Again this is no exception. I never met Prof. Grad, but just by reading his paper, in particular, 1952 paper, I think he is good person. He shared his frustration. Better read it.

And then I will talk about Prof. B. C. Eu later on. All others, European. They are chemists. I will talk about why I brought them. The last person is mathematician, Levermore. He is a student of Lax. Do you know P. D. Lax? The famous hyperbolic system. He is originator of hyperbolic system. Riemann problem, modern CFD relying on basically his theory and so on.

This is to me history of RMG. Navier, Fourier, Maxwell, Boltzmann. You all know them. Why Gibbs? I will explain why. And then, Onsager, Prigogine, I think Gibbs, I don't think Gibbs, but Onsager, Prigogine won Nobel prize, in not physics, it is in chemistry. Why in the world RMG somehow something to do? Because, as I told you, in fundamental level, either movement or interaction. Interaction, there is dissipation, dissipation needs irreversible thermodynamics, that comes with that. So Prigogine won the Nobel prize by explaining dissipation. Some similar one is Onsager.

And then following their works, Muller, Jou, Eu. Eu, Jou, Muller, they are competing each other. They somehow work on same subject, we call physical chemistry, irreversible thermodynamics, forgotten in modern chemistry. They are working on all kind of other things. Still conceptually very touch problem. It is area of statistical mechanics and so on. I found very interesting.

On the other hand, the next line is mathematically oriented. I am not saying Chapman is only mathematician, probably physicist and so on. But, to me, their approach is more like mathematically oriented. Chapman, Enskog, Grad, Truesdel, Cercignani, Ruggeri, Levermore, Villani. I think the last three persons still live. Cercignani passed away several years ago. On the other hand, Ruggeri is Italian mathematician. He is still publishing. Levermore, he is student of P. D. Lax. He proposed, we call, Gaussian closure. I will explain what that means.

RMG, there is mathematician group, physicist group, chemist group, like me engineer group. It happens to be, I was somehow one of the best positioned in contacting all of them. Somehow I was lucky enough. Prof. Roe provided initial contact with mathematician. Chemist, somehow, I myself somehow open channel through books and so on. Physicist same thing. So anyway.

Villani is mathematician, I think, he won Fields medal about seven or eight years ago. Why in the world mathematics give Fields medal to this subject? Because Boltzmann equation. Their interest is not ours, they are interested in well-posedness of Boltzmann equation, in particular, for some potentials. P. L. Lions. Villani, he is very young, he is celebrity, very popular in France. You better read his book. He wrote one summary of Boltzmann equation from mathematical viewpoint. Very good. I think he is thirty something. He is more like genius. He is mathematician. Cercignani, I do not need to introduce him. There are several books.

My approach is somehow very different from theirs.

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I will tell you this. Thermodynamics is a funny subject. The first time you go through it you don't understand it at all. The second time you go through it you think understand it except for one or two small points. The third time you go through it you know you don't understand it but by that time you are so used to it, something like that.

This is typical. I mean I think you all agree. Because in sometime of thermodynamics class why we have to learn thermodynamics? In the end, we will not use it, right? Except efficiency cannot be higher than 100, something like that. That is only place the second law of thermodynamics comes in. Why bothers, why tests it, that kind of thing? I agree. I will show you, that is not story in RMG. It plays a critical role.

And then, most of mathematician, in their career, they were never exposed to thermodynamics. They don't know why this one. It will make big difference. That is why I chose chemical viewpoint over mathematical viewpoint. Because I always train engineers likely nature rather than conceptual so on. That is, anyway, the way I think. Anyway, second thermodynamics, you will see importance of this one.

By the way, this Prof. Truesdel, he is very very interesting person. You can see he is joking. Try to read it. Anyway, he jokes about those persons, Onsager, Prigogine, Gibbs, and so on. They are fighting each other. Mathematician, they think why we need thermodynamics?

Mathematicians like freedom.

Chemist, on the other hand, they believe in nature. Nature always gives you laws. They believe in conservation laws, they believe in theory of relativity something like that. They believe in 1st law and 2nd law of thermodynamics.

There is fundamental gap between chemist and mathematician. You did not know that, right, this kind fighting. But, to me, immediately after I entered this, I sensed that. Therefore, somehow, I am opponent of mathematicians, even though I brought many good things to mathematics. I can sense that. It's all right. But, if I choose one, I will take chemistry, because we are talking about the equations trying to describe nature. Unless you question fundamental laws like the 2nd law of thermodynamics, you must honor it.

This is the Navier-Stokes I already told you. This is the Navier constitutive law. The important one is, it is equal, but actually assignment. When you determine the viscous shear stress, you basically rely on two informations; one is eta, viscosity, typically a function of temperature, also gradient of velocity. That's it. That is the most important one. Anyway, that is the first (order) law.

On the other hand, there is Boltzmann kinetic equation. I deliberately avoid mentioning these things, I will explain why in the last page, because, once you look at this detail, you lose something, because it is complicated term. You don't need to do so. More important thing is, oh, there is star, there is no star. I will explain what that means. You have to look at this term that way. There is star, but other term is no star.

01:10:25

Anyway, I just collectively say it is C collision, based on binary collision. One to distribution function of first particle, second one. That is it. Just I will use C. That is it. There, dissipation occurs, you have to worry about the second law of thermodynamics, it is complicated. Anyway, that is it. All I need is this is kinematical term. I carefully manipulate this term. That is Boltzmann equation.

So that equation is 1872 after 1822, there is gap, 50 years. Why in the world without this equation? Because this equation derived not from this kinetic equation, but some based on integral calculus and so on. This is empirically derived equation while it is beautiful equation. This is not the same as conservation laws, because you put constitutive equation. When you use this kind of equation, there is assumption comes in. Again underlining assumption. This is first-order linear world.

RMG, you have to, not necessarily abandon, but more like onion, you live with one layer. Onion has many layers. This is first-order you feel comfortable. You are trying to second-order. It should be smooth. Important one is your theory must be smooth transition. Navier-Stokes must be inclusive. Sometimes those mathematically beautiful theories, but they fail miserably in that test.

Therefore, after 50 years, later, kinetic equation, people's understanding of gas improved. There is molecular one, this is continuum based on. This is prof. Grad. Again you will see again his derivations. This is history. Truesdel, he is very influential person. He actually established several journals including Journal of Rational Mechanics. When I first confront with the title, I doubt why we need rational. What that means? What that means? Rational mechanics. That means there is irrational mechanics. To me that's very strange. That is his philosophy. To him, his theory is rational, all others are maybe irrational. I don't know. That's very powerful journal.

There are many followers. Nothing wrong with it. In science and engineering, that is typical. Because diversity is required. Let them people try many things.

This is, to me, first encounter to B. C. Eu. He is chemist. Now he is old, almost 80 years old. After PhD, I luckily won NRC research associate in NASA Goddard.

01:13:57

I remember vividly one time. Because it is huge institute. Good thing about the research associates is, let them allow whatever they want to do. Two years basically is just my individual, freely go to library, meet someone and so on, so virtually no restriction. I pick up subjects I found interesting. But I belong to scientific computing, in particular, space plasma. Plasma is rarefied state. So again I kept that challenge from my colleague, failure of Levermore's Gaussian closure.

One typically after lunch, at that time, there is no internet freely available. Therefore I have to visit again library. That center library is big. I typically check first probably AIAA journals, and then Physics of Fluids, JCP, and then typically I ended up to some mathematical journals, later on physics journals too, there is fluid section, Physical review E. One lunch time, pick up most recent PRE, that was 1998. I quickly through looking at the title, the topic I like. One that particularly I found shock wave. Remember my phd topic was shock wave in Riemann problem. So I found that name was shock wave and generalized hydrodynamics.

What is difficult, I looked at and open that page. Just immediately read abstract and I show the figures, I found something very very interesting. Because I know in the shock calculation, people talking about shock density inverse thickness. Remember the shock thickness is 10 microns, very thin, in that small region, how steep density is very important. In particular journal paper, they somehow seem to present the first shock calculation beyond Navier-Stokes, seem to me just overcoming Grad' 1952 failure.

So I was so excited, just copy that one, and then I spent about one month in that, in order to learn that paper, and then, of course, references I found 10 or 20. And then I read them all. I realized oh this is something I can do. I can bring this knowledge to engineers. And then I checked authors. First one is Al-Ghoul, strange middle-east, but second one is Eu, so Eu. EU is European. So I thought he is European. No internet at that moment. Anyway, I thought some European guy. And then check internet. 1998, there is internet available. I found he is Korean-American (Korean-Canadian), very old. He is chemist. I never thought (him chemist) and never met (him), anyway, until a couple of years later. So that person is prof. B. C. Eu.

Because he was so influential in my research, ten years ago I invited him to my university. There were lectures and still collaboration. We didn't publish anything as co-authors. Nonetheless, academically I respected him and learned a lot. He is B. C. Eu. This is physical review E. Oh, reverse, not shock wave, but generalized hydrodynamics and shock wave. So Physical Review E.

And then my supervisor, Prof. Roe. I learned from Prof. Roe, I think, two things, anyway, he still keeping his work. Not like any professor in big university, if you have big research group, normally you rely on phds and postdocs. You stop working by yourself. Only checking final output, only just revising final manuscript and submit it, like Prof. Roe, no one will reject it, unless there is serious mistake, that is typical one. Prof. Roe is not that style, he is still working by himself, in many cases he publish as single author. Anyway, that is one thing I learned. That is because I am trying to do similar things.

01:19:17

In the case of liquid, in my lecture, I deliberately avoid mentioning liquid, even though microfluidics nanofluidics people use both. The reason I deliberately distinguish is simple. As I emphasize I am interested in mesoscale, if you look at molecular level of liquid and gas, they are different. One most significant difference is, if you look at small scale, gimbal, sphere, collide and move very long distance, even though there are many many many particles, until another collision. That is, we call, mean free path. Typically, in gas, when you define the degree of rarefaction, it is, we call, Knudsen number based on that one, in comparison with characteristic length.

How about liquid? You cannot define Knudsen number. I will talk about these things. Which means there is no guideline. I mean, that doesn't mean I am not thinking liquid. I am very interested in liquid, too. The reason is I don't have time to do so. Also, too difficult in the fundamental level.

But one thing I'd like to point out, in particular, mesoscale description, one thing is free volume. Because, in liquid, you have molecules, they are so compact, therefore, we have one ball, one ball, there is empty space, they become important, so, that we call free volume. Free volume play a critical role in modeling liquid. That's a critical difference. In gas, we don't have such free volume. You don't have to worry about it. That is big difference.

Other than that, probably surface tension. I am just talking about what are new things from ordinary scale to micro- nano- scale in the case of liquid. There are two things. If you take in account, there were two things, surface tension, and free volume, and then, in many cases, you can handle that, at least, from the modeler's viewpoint. Unless you are talking interface, that is small scale, liquid particle, solid wall atomic interaction, that will require MD simulation and so on, assign some potentials. You have to monitor what they are doing.

Other than that, in particular, continuum level, not much difference from gas. In that sense, gas even that's simple, it is challenging. Because you have to worry about those high Knudsen number effects and so on. That is one thing I'd like to mention.

Another one is some of you are working on hypersonic case, that is chemically reacting gas. What that has to do with this one is I am talking about fundamentals. How to use this lecture, if you are interested in chemically reacting, then you can add as first case vibrational non-equilibrium. So you can add another equations, taking into account vibrational mode, typically 700K and so on in that case. In monatomic gas, you don't have any vibrational mode. But, in diatomic gas, you have to put those vibrational modes.

Other than that, dissociation, all kind of complexities. It's too complicated. In many cases, you can use just Navier-Stokes and so on. In our case, you may use 2nd-order conservation laws with vibrational mode equation, and some multi-species and so on. You can do basically the same thing, what you do to Navier-Stokes.

OK. Back to this slide. There was the first encounter with Prof. Eu. Because his theory is not easily understandable to me, at least. I emailed a lot. And lucky enough, he found me, also, somehow, he said I am the first person to try his theory. Therefore somehow he responded every time when I had some questions. That took a couple of years. And then I almost understood his theory and then applied to my problem and so on.

Anyway, he right now retired. He published, I think, 5 or 6 monographs and one textbook. This is one monograph, non-equilibrium statistical mechanics, ensemble method. This is not engineering book, not mathematical book, but chemistry book. But some concept is explained in this book. Anyway, I found preface of this book very impressive. Whenever my work is rejected and I am disappointed, I read this one.

OK, applications, high-altitude flying vehicles, micro sensors and actuators, many. Recent application would be, this is traditional one, OLED, organic light emitting diodes deposition devices. This is modern scheme. That relies on those depositions of particular type of complex molecules. How they manufactured these things, one way to do it is to make near vacuum, let those complex molecules, gases, somehow deposit on the surface of some devices. Also, exactly the same theory can be applied to not gas molecule, but electron transport in semi-conductor. Many mathematicians are working, in particular, European. You can apply exactly the same theory of gas dynamics to this problem.

Challenges, as I told you and explained, it is unknown problem. Not easily testable. Theoretical barriers, not only governing equation but boundary condition. Typically second-order governing equation, it, sometimes, takes more than one page. You have to, just equation is two pages, you have to solve it. That's huge challenge. There might be many bugs, you don't know what's happening there, that's problem. That's challenge. Also cross-disciplines, not only fluid dynamics, but also mathematics, chemistry, and so on. Many disciplines are required to understand this kind of problem.

That was first lecture. By the way, any questions for lecture one? Could you once again what is mesoscale?

Mesoscale, mesoscale means, you understand microscale, which is molecular level, macro is continuum scale, let say centi-meter and so on. Mesoscale means between, bridges two worlds, that is mesoscale, mesoscale. Micro means sub-atomic, amstrong, nano-scale you are talking about. Macro means centi-meter and meter. Mesoscale all of things between them.

In nature, everything we call complex system. In the case of gas, you have gas molecule. In the case of granular flow like sand, you have maybe one milli-meter-size dust, the granular flow, very famous one. You go to beach, try it, you have dust, making mountain like this one, suddenly at particular angle, it just collapses. That's very famous problem, very difficult to predict. Complex system means that individually you can understand it, like MD, just Newtonian equation, you solve it. Collectively, there is funny thing, very strange thing happens, very difficult to understand. In nature, everything is complex system.

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