# Professor Keenan's Contribution to Thermodynamics

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**Abstract.** Professor Keenan's engineering contributions to thermodynamics, such as the development of the properties of steam, are world-renowned. His contributions to the science and the teaching of the subject, however, will probably have a longer lasting influence. All of his contributions derived from an uncompromising search for understanding and elimination of ambiguities overlooked or accepted by others. He developed a coherent and logical exposition of the fundamentals of thermodynamics so that the widest possible range of problems could be considered in a uniform and consistent manner. The way Professor Keenan was able to convey to his students but also to his colleagues what he believed about the concepts in thermodynamics, was to ask questions.

Mr. Chairman, Professor Sharp, ladies and gentlemen, this is a great privilege for me, to talk to you a little bit about Joseph Keenan, my mentor, my friend and the person that guided me not only in thermodynamics when I was a student, but later on as I tried to create businesses. His intuition in all endeavors was outstanding and he always led me the right way. President Hockfield talked a lot about Professor Keenan's achievements and I could add a lot more to it right now, but I thought maybe I will give you a very short example of the kind of reputation that Professor Keenan had around the world.

By the way, let me interject right now that yesterday I promised the next speaker, Professor Bedeaux, that I'm going to be as short as possible in my speech so that Professor Bedeaux has enough time, not only to develop his position in statistical mechanics, but also to allow enough time for a discussion. For Professor Keenan the discussion following a lecture was the key to successfully conveying or receiving information.

Back in the late fifties, I was an assistant professor working in thermodynamics under the direction of Professor Keenan. One day he told me "I've been invited to give lectures in England at Cambridge University. Come with me and give some lectures too." So we went there and I was very stunned to find out not only that they were teaching thermodynamics at Cambridge University from his book, but actually a lot of the things that were going on in his class and in the MIT Department of Mechanical Engineering were adopted there. So I went to the head of the department, Professor Hawthorne, more accurately Professor Sir William Hawthorne because the Queen two years earlier had awarded him knighthood for his work in thermodynamics, and said to him "Professor Hawthorne, I'm very surprised that what you're doing in thermodynamics here sounds to me very much like what we're doing at MIT." And he turned to me and said "Mr. Hatsopoulos, aren't you aware that Cambridge University was Keenanized in 1942?"

I will show you some videos where Professor Keenan makes some remarks on when we talked about things. And you may notice in that video I am going to play, that there is a stack of books, you cannot see the titles very well, but they are all the same book in

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different languages Russian, German, French and other languages. They are all the 1941 book of Joseph Keenan [1], the one that President Hockfield mentioned earlier.

I would like to describe another anecdote that may amuse you. Right after the oil embargo of 1973, we were all very concerned on how to improve efficiency of energy use in the United States. And in fact, I don't know how many of you are aware that even now, but more so back in 1973, the lowest industrial efficiency use of energy in any country is in the United States. The efficiency of use in US industry in 1973 was close to about 11%, although it could theoretically have been as high as 95%. All other countries, especially Japan and Germany, had efficiencies of energy use in industry which was much greater than that in the United States. So anyway, a number of us representing several companies were testifying in Congress. One of the items we wanted to convince members of Congress was to change the regulation dealing with utilities. And the reason for that was that we thought we could use something used quite extensively in Europe but never in the United States, which today is called cogeneration. In cogeneration you basically use energy twice: first to produce electricity at higher temperature and then you use the heat which is rejected at a lower temperature for other purposes. The term "cogeneration" was coined at that meeting by my colleague from Dow Chemical. So anyway, we testified several times in Congress and congressmen were very dubious about what we were talking about. They thought we were trying to pull a fast one.

They said how can energy be used twice? We understand you can use energy once and that's it. How can you use it twice? We testified twice unsuccessfully before I went to Professor Keenan and said, "You know, Joe, we have that problem. We can't convince congressmen how we use energy twice." He said to me "You have to teach them a little thermodynamics. At first you use only a fraction of the fuel's energy to produce electricity and a larger fraction of another property of the fuel called "availability", which in effect, is the high-quality energy. What is left is a substantial amount of low quality energy which can be used for heating purposes." So my colleagues from other companies and I, after visiting members of Congress several times, we convinced them to enact the Public Utility Regulatory Policies Act of 1978 (PURPA) and cogeneration became a reality in the United States.

Now, I want to mention that Professor Keenan was extremely strict with the use of words, not only in writing but in speaking. I like to replay with you a very short video from the one that is on the website [2], just one minute of it, when he makes a comment to me [3].

> JOE KEENAN: Now you're using the term energy in a non-thermodynamic sense.
> HATSOPOULOS: That's right.
> KEENAN: And we might mention that it's the popular name for something which in thermodynamics is named something else.
> HATSOPOULOS: That's right.

You see, he always would say things like that if a student ever dared call something the wrong way like I did at that point when he commented, and that was just a few months before he passed away. His daughter, Esther Keenan Carr, who is here today, was videotaping these remarks. In the course of the interview, I used the word energy for what we know as availability in thermodynamics. By the way, availability is the

term coined by Joseph Keenan for a concept developed by J.W. Gibbs. It stands for low-entropy energy. Incidentally, not only students feared Professor Keenan's criticism for the wrong use of words, but actually the whole MIT faculty was fearful that when they spoke on any subject they might use a word that was not appropriate for what they meant. Maybe Professor Gyftopoulos who will speak at lunch about Professor Keenan could cite an example of what I mean by having Professor Keenan always criticizing the whole MIT faculty when they used the wrong word for something they meant.

The way Professor Keenan was able to convey to his students but also to his colleagues what he believed about the concepts in thermodynamics was to ask questions. And with that I want to play another part of the video we recorded with Esther Keenan.

> KEENAN: I think there was another question I brought up too. I had been to a meeting in New York where Zemansky was present and I never felt I understood the statistical thermodynamics. And I asked questions of those people. And I said now why, if you have the gas in half the box confined with a partition and a vacuum in the other half, why is it that the entropy increases when you lift the partition? And they said well, it increases because of the enormously greater number of states that are available to the system as soon as the partition is lifted. And I thought about this and I said but this opens an interesting question. Suppose that I have a partition that I can open very quickly and close very quickly. I open it. Immediately the entropy is increased to what it would be if the gas filled the whole box. But suppose with my high-speed equipment I quickly close the partition and only a little of the gas had managed to get through in the meantime? And so the gas had not uniformly distributed itself through the box. Now if you examine the entropy you find that it is greater than it was when the gas filled only half the box, but not nearly as great as when it fills the whole box. Therefore my closing of the partition resulted in the decreasing of the entropy.
> HATSOPOULOS: And a violation of the second law.
> KEENAN: Yes. An adiabatic decrease of entropy of the system is a violation of the second law. And how do you explain that?

Well, you can see an example of the questions he kept asking everybody. That was his technique. And it sounded to me, when I first was exposed to it, like the Socratic Method. That is what Socrates was using in the dialogues and symposia he was participating with Plato and others in the fifth century BC. As recorded by Plato, what Socrates was doing was convincing his audience by asking questions, convincing his audience that his theories were correct. In other words, in effect he was selling his ideas by asking questions.

The difference between Professor Keenan and Socrates was that Professor Keenan was not only conveying his concepts to the audience by asking questions, but he was really provoking his audience to create ideas. In other words his questions were both instructive and eliciting creativity. He was trying to get his audience to produce something and he succeeded and, therefore, I think that Professor Keenan (I'm sure that a lot of Greeks in the audience will be upset by what I'm going to say); in some ways Professor Keenan was better than Socrates . . . , I apologize.

So basically I started thinking, what would Professor Keenan say if he was present

here? And I thought about it quite a lot the last few days and I think the first thing he would say is to thank you all for taking the time to come and talk about thermodynamics. Because he would think that this is a great thing you did for thermodynamics and for him. But the second thing he would do is to ask you a question. So I wondered what kind of question he would ask if he read the program and heard all the speeches that will be given, what kind of question he would ask all of you. I thought about this in the middle of the night several days ago. My guess is he would ask all of you the following question: "Do you believe that entropy is an intrinsic property of any system, whether macroscopic or microscopic, whether in a state of equilibrium or in a state of non-equilibrium?" Before answering you might wander what he means by entropy. Because many of you may ask "How can you define entropy in a non-equilibrium state?" or "How can you define entropy in a system that has one molecule?" Well, I looked up the encyclopedia Britannica in the article on thermodynamics.

UNKNOWN VOICE: Was not Professor Keenan the author of the article [4]?
HATSOPOULOS: Yes, that's right. He was the principal author of that article.

So the definition is as follows. I'm reading: *Entropy is the measure of a system's energy that is unavailable for work.* Now obviously that definition applies even to a non-equilibrium system, especially in a non-equilibrium system. And all of us know that you get work out of a system in a non-equilibrium state – a flywheel that turns, something that explodes, even a single molecule that moves about. You may not get all of its energy in the form of work, but you get work. So the definition of entropy is the measure of the system's energy that is not available for work.

I would very much appreciate, as he would, if during the presentations of the next two days you ask many questions.

## REFERENCES


1. J.H. Keenan, *Thermodynamics*, John Wiley and Sons, 1941.
2. The symposium web site http://mit.edu/keenansymposium contains the full trascription and a selection of video excerpts of the interview that Keenan's daughter Esther Keenan Carr taped a few months before Joe passed away. The "Autobiographical Notes" by Keenan in this volume are based on the same interview.
3. Videos of this and the other talks, and of all the discussions that took place during the Symposium can be viewed at http://mitworld.mit.edu/series/118/
4. J.H. Keenan, G.N. Hatsopoulos, and E.P. Gyftopoulos, "Thermodynamics," entry in the 1974 of the *Encyclopedia Britannica*, pp. 290-315, and several subsequent editions.