Proceedings of Meetings on Acoustics

Volume 8, 2009 http://acousticalsociety.org/

158th Meeting
Acoustical Society of America
San Antonio, Texas
26 - 30 October 2009
Session 4pED: Education in Acoustics

4pED3. The Rubens tube

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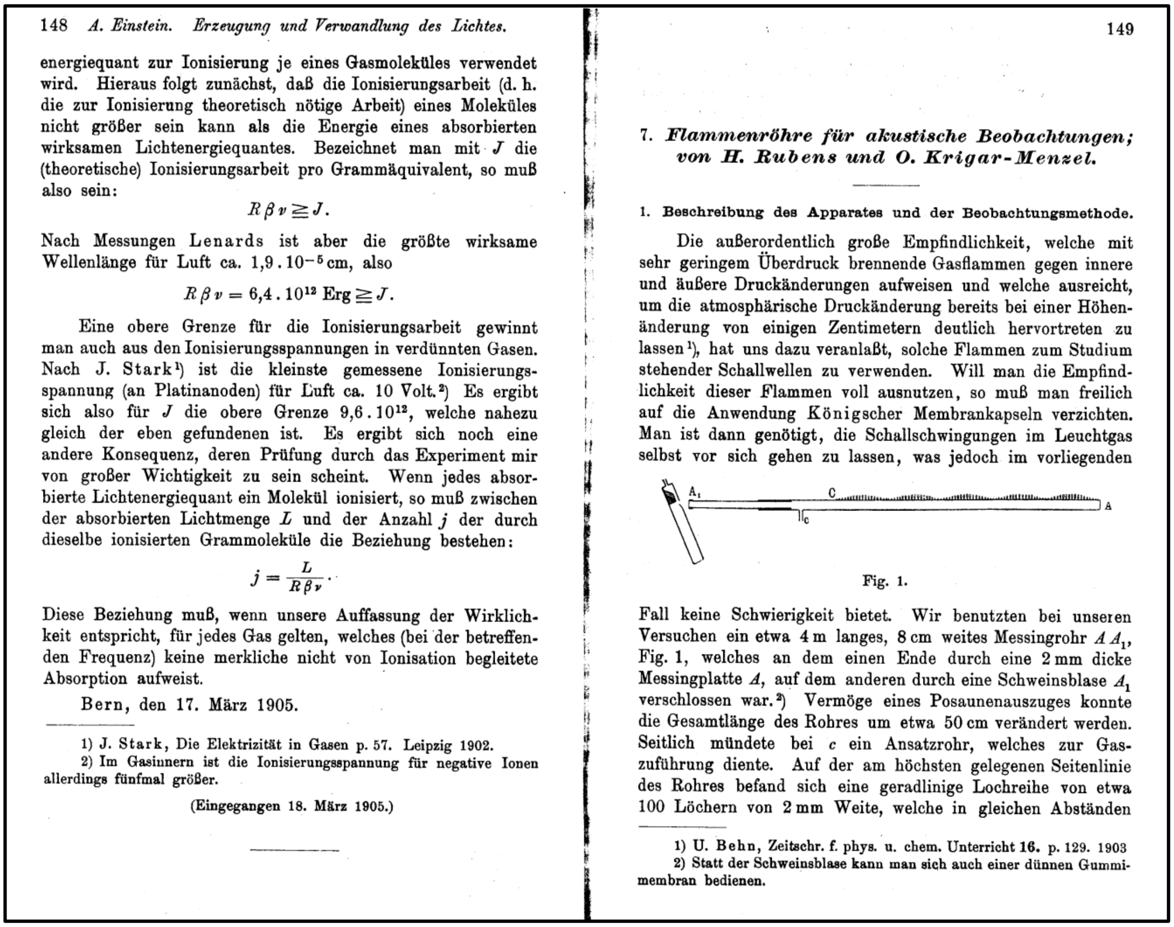
In 1905, Heinrich Rubens and Otto Krigar-Menzel published a paper describing a unique acoustics teaching apparatus. They developed a flammable gas-filled tube with holes in the top that revealed the acoustic standing wave behavior via the height of flames above the tube. Interestingly, their article holds the distinction of being printed immediately following Einstein's Nobel-prize winning paper on the photoelectric effect. From that auspicious beginning, the "Rubens tube" has been used for over a century in the teaching of acoustical resonance behavior. This article describes some of the history around the tube's development and its operation, as well as some of the commentary and investigations involving the flame tube found in the literature.

Published by the Acoustical Society of America through the American Institute of Physics

[DOI: 10.1121/1.3636076]
Received 18 Jul 2011; published 21 Aug 2011

1. Flame Tube History

In 1905, an article was published in *Annalen der Physik* that has impacted literally millions of science students. I refer not to Einstein's article on the photoelectric effect, but the innocuous paper that, coincidently, immediately followed Einstein's famous article. In the article, Heinrich Rubens and Otto Krigar-Menzel[1] discussed the development and underlying principles of a physics demonstration that has come to be known by various names, including the "Rubens tube," "flame tube," and "standing wave flame tube." Note that Rubens had published an initial description of the tube previously, in 1904.[2] The last page of Einstein's article and the first page of Rubens and Krigar-Menzel's article are displayed in Fig. 1.



148 *A. Einstein. Erzeugung und Verwandlung des Lichtes.*

energiequant zur Ionisierung je eines Gasmoleküles verwendet wird. Hieraus folgt zunächst, daß die Ionisierungsarbeit (d. h. die zur Ionisierung theoretisch nötige Arbeit) eines Moleküles nicht größer sein kann als die Energie eines absorbierten wirksamen Lichtenergiequantes. Bezeichnet man mit J die (theoretische) Ionisierungsarbeit pro Grammäquivalent, so muß also sein:

$$R\beta\nu \geqq J.$$

Nach Messungen Lenards ist aber die größte wirksame Wellenlänge für Luft ca. $1{,}9 \,.\, 10^{-5}$ cm, also

$$R\beta\nu = 6{,}4 \,.\, 10^{12} \text{ Erg} \geqq J.$$

Eine obere Grenze für die Ionisierungsarbeit gewinnt man auch aus den Ionisierungsspannungen in verdünnten Gasen. Nach J. Stark[1]) ist die kleinste gemessene Ionisierungsspannung (an Platinanoden) für Luft ca. 10 Volt.[2]) Es ergibt sich also für J die obere Grenze $9{,}6 \,.\, 10^{12}$, welche nahezu gleich der eben gefundenen ist. Es ergibt sich noch eine andere Konsequenz, deren Prüfung durch das Experiment mir von großer Wichtigkeit zu sein scheint. Wenn jedes absorbierte Lichtenergiequant ein Molekül ionisiert, so muß zwischen der absorbierten Lichtmenge L und der Anzahl j der durch dieselbe ionisierten Grammoleküle die Beziehung bestehen:

$$j = \frac{L}{R\beta\nu}.$$

Diese Beziehung muß, wenn unsere Auffassung der Wirklichkeit entspricht, für jedes Gas gelten, welches (bei der betreffenden Frequenz) keine merkliche nicht von Ionisation begleitete Absorption aufweist.

Bern, den 17. März 1905.

1) J. Stark, Die Elektrizität in Gasen p. 57. Leipzig 1902.
2) Im Gasinnern ist die Ionisierungsspannung für negative Ionen allerdings fünfmal größer.

(Eingegangen 18. März 1905.)

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7. ***Flammenröhre für akustische Beobachtungen; von H. Rubens und O. Krigar-Menzel.***

1. Beschreibung des Apparates und der Beobachtungsmethode.

Die außerordentlich große Empfindlichkeit, welche mit sehr geringem Überdruck brennende Gasflammen gegen innere und äußere Druckänderungen aufweisen und welche ausreicht, um die atmosphärische Druckänderung bereits bei einer Höhenänderung von einigen Zentimetern deutlich hervortreten zu lassen[1]), hat uns dazu veranlaßt, solche Flammen zum Studium stehender Schallwellen zu verwenden. Will man die Empfindlichkeit dieser Flammen voll ausnutzen, so muß man freilich auf die Anwendung Königscher Membrankapseln verzichten. Man ist dann genötigt, die Schallschwingungen im Leuchtgas selbst vor sich gehen zu lassen, was jedoch im vorliegenden

Fig. 1.

Fall keine Schwierigkeit bietet. Wir benutzten bei unseren Versuchen ein etwa 4 m langes, 8 cm weites Messingrohr AA_1, Fig. 1, welches an dem einen Ende durch eine 2 mm dicke Messingplatte A, auf dem anderen durch eine Schweinsblase A_1 verschlossen war.[2]) Vermöge eines Posaunenauszuges konnte die Gesamtlänge des Rohres um etwa 50 cm verändert werden. Seitlich mündete bei c ein Ansatzrohr, welches zur Gaszuführung diente. Auf der am höchsten gelegenen Seitenlinie des Rohres befand sich eine geradlinige Lochreihe von etwa 100 Löchern von 2 mm Weite, welche in gleichen Abständen

1) U. Behn, Zeitschr. f. phys. u. chem. Unterricht **16**. p. 129. 1903
2) Statt der Schweinsblase kann man sich auch einer dünnen Gummimembran bedienen.

Figure 1. The last page of Eintsein's article on the photoelectric effect in Annalen der Physik and first page of Rubens and Krigar-Menzel's article.

A. What is the Rubens tube?

The Rubens tube is a means by which acoustic standing waves in a pipe can be visually demonstrated. Several small holes are drilled at regular intervals in the top of the tube and flammable gas is injected.

Once the gas exhausting through the holes is lit and an acoustic standing wave is produced, variations in flame height result. Rubens and Krigar-Menzel's original tube (see Fig. 1 for a schematic) consisted of 100 2-mm diameter holes drilled across the top of a round brass tube 4 m in length and 8 cm in diameter. The tube, closed at both ends, was filled with coal gas and flames were lit from the gas exiting through the holes at the top of the tube. They drove their tube at resonance using e.g. a tuning fork or an organ pipe, which produced variations in flame height that correlated with the acoustic standing wave pattern inside the tube. A more modern version, used in a recent paper by Gardner *et al.*[3], is displayed in Fig. 2, with an example of the flame response in Fig. 3.

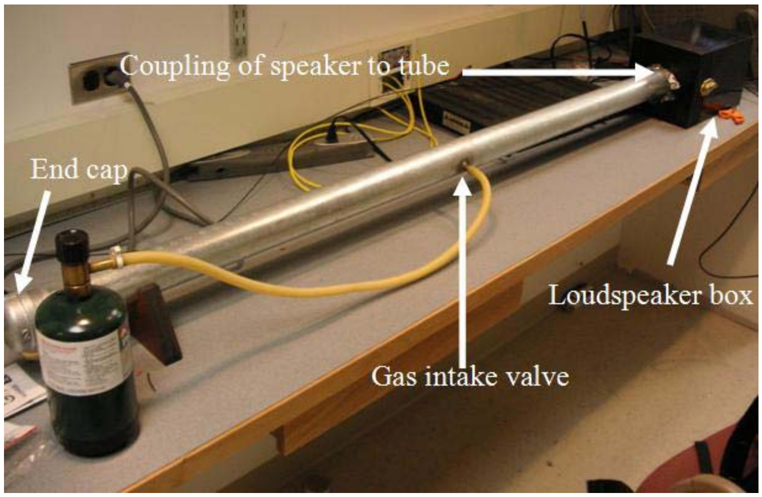

Figure 2. Rubens flame tube example from Ref. 3.

Figure 3. Flame tube in operation.

B. Who were Rubens and Krigar-Menzel?

Heinrich Leopold Rubens (1865 – 1922) was a German physicist at the Humboldt University of Berlin who was directly involved in the formulation of quantum theory. He performed the experiments that resulted in Planck's initial quantum hypothesis and, subsequently, Einstein's Nobel-Prize winning interpretation of the photoelectric effect. Below in Fig. 4 is a photograph[4] of Rubens with other attendees at the historic, by invitation-only, first Solvay Conference in 1911. Rubens is standing third from the left. (See Wikipedia for a complete legend, but others pictured include Marie Curie, Max Planck, Albert Einstein, Maurice de Broglie, and Arnold Sommerfeld.)

Rubens's doctoral advisor was Dr. August Kundt, the significance of which is described subsequently. Also of note is that one of Rubens's students was Gustav Hertz,[5] who received his doctorate in 1911 and went on to receive the 1925 Nobel Prize in Physics for his role in the famous Franck-Hertz experiments. Thus, Rubens's career can be linked directly to two Nobel Prizes in Physics.

Figure 4. Photograph of 1911 Solvay Conference attendees. Rubens is standing, third from the left. For reference, Einstein is also standing, second from the right.

Otto Krigar-Menzel (1861-1930), was a German theoretical physicist in Berlin. Of perhaps particular importance to acousticians is that Krigar-Menzel was a student of Helmholtz and edited his series of lectures on dynamics. Aside from his role as editor, Krigar-Menzel is perhaps best known for his part in experiments between 1884 and 1896 to find the gravitation constant and mean density of the Earth.[6] The results found were to within less than 0.2% of the current accepted values.

C. Tube precursors

As mentioned previously, Rubens's doctoral advisor was August Kundt. It is likely that a portion of Rubens's interest in developing this demonstration stemmed from having directly observed his advisor's work. In 1866, nearly 40 years previous to Rubens and Krigar-Menzel's paper, Kundt[7] reported on the development of another standing wave demonstration. Now known as the "Kundt tube," the tube is filled with cork dust or other fine powder and driven at resonance. At resonance, the cork settles at the particle displacement nodes (pressure antinodes). (Note that the fine-scale motion of the dust was foundational to Rayleigh's work on acoustic streaming.[8]) A graphical description of Kundt's observations are shown in Fig. 5.[7] Another important precursor to the Rubens tube was the paper published by Behn in 1903,[9] in which the sensitivity of flames to variations in ambient pressure is described. Thus, Rubens and Krigar-Menzel essentially combined the results of Kundt and Behn in developing this visually impressive demonstration.

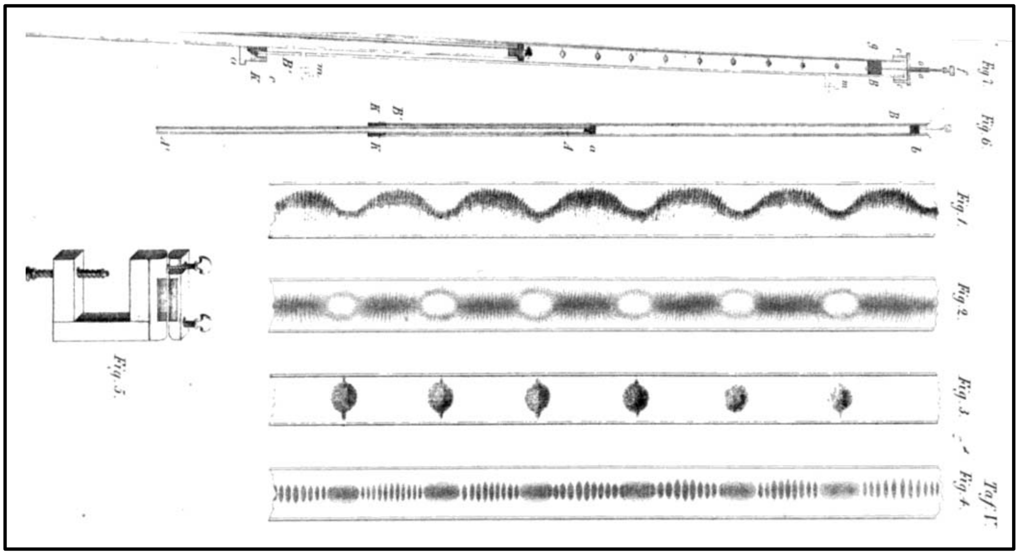

Figure 5. Figure from Kundt's 1866 paper describing his standing wave demonstration.

2. Its Use and Variations

A. Its dissemination to the classroom

Enthusiasm for the Rubens tube quickly spread. The first citation to the acoustics demonstration appears to be in 1907, when Behn[10] gave reference to Rubens's 1904[2] and Rubens and Krigar-Menzel's 1905[1] papers in describing additional experiments on his version of the flame tube, which was constructed to examine changes in ambient pressure due to height or pendulum-like tube motion. Shortly thereafter, Waetzmann[11] described a Rubens tube apparatus with adjustable plungers to demonstrate interference of sound waves in tubes of various lengths. From that time, the dissemination of the flame tube concept was aided by descriptions that appeared in physics demonstration collections by Sutton[12] and Meiners[13] and introductory physics textbooks by Halliday and Resnick[14] and Sears and Zemansky.[15] As described subsequently, commentary and studies on tube behavior appeared in publications dedicated to physics teaching: *The Physics Teacher* and *The American Journal of Physics*. In recent years, videos of its operation, including a Mythbusters TV show segment, have appeared online. A recent internet search of "Rubens tube" and "video" yielded more than 114,000 hits.

B. Variations

Although there are many variations on flame tube design, some significant innovations merit specific mention. First, Daw[16, 17] published articles describing the construction and use of square and circular flame tables. These were intended to show two-dimensional standing wave patterns in different coordinate systems. Second, Coleman[18] described how an air track system could be temporarily modified to become a flame tube setup. This could be advantageous in situations where storage space or budget preclude having two separate apparatuses.

3. Phenomena Explained

A. Where do flame maxima occur?

One of the natural questions that arise during the presentation of this demonstration is that of the location of the flame height maxima. Do they occur at pressure nodes or antinodes? Why? The answers to these questions have been the subject of a fair amount of debate and discussion within the physics teaching literature. To review what some have said, Rubens and Krigar-Menzel[1] originally suggested that maxima could occur either at pressure nodes or antinodes. Sutton[12] stated that maxima would occur at an antinode. Halliday and Resnick[14] described maxima occurring at a displacement antinode (pressure node), which Meiners[13] agreed with. The confusion prompted Iona[19] in 1976 to write a letter to *The Physics Teacher* asking for further explanation. In a response, Rossing[20] described normal operation as having tall, yellow flames at the pressure nodes and short, blue flames at the pressure antinodes. Thus, the flame maxima are at the pressure nodes. However, Rossing suggested that high sound intensities (140-150 dB) and time-averaged pressure variation due to nonlinearity could cause the operation to change. Bauman and Moore[21] also responded to Iona and suggested that the static gas pressure was critical in determining where the flame maxima occurred—"normal" operation was to have flame maxima at the pressure nodes, but at low static gas pressures, the tall yellow flames could dip below the height of the shorter, blue flames at the pressure antinodes. Thus, by the late 1970's the understanding was that Rubens and Krigar-Menzel's original assertion was correct: flame maxima could occur at nodes or antinodes. Furthermore, although normal operation was to have the flame maxima occur at nodes, the sound intensity and/or static gas pressure could impact the operation.

It was with this background that Ficken and Stephenson[22] approached their study of the flame tube operation. They used a simple model based on the (incompressible) Bernoulli equation to determine the mass flow rate out the holes along the tube. They showed that the time-averaged mass flow rate is greatest at the holes corresponding to pressure nodes for the normal operating condition. As the gas static pressure was reduced or acoustic levels increased, they observed a "reversal" in flame height—flames were greater in height at the antinodes than at the nodes. By holding a burning cigarette above the tube holes and by shining a laser in the tube through small windows, they observed an intake of unburned gas and possibly air at the antinodes, which they referred to as "gulping." They indicated that the gulping is caused by the acoustic oscillations being greater in amplitude that the static pressure flow, which results in a temporarily negative (inward) mass flow rate during the rarefacting wave near the antinodes.

Ficken and Stephenson[22] have offered the most complete explanation of tube performance to date, but further quantitative experiments of this phenomenon and perhaps use of the compressible Bernoulli equation in their model could be explored. Even after they published their paper, some debate, confusion, or perhaps a simple lag in understanding continued, as evidenced by the paper by Jihui and Wang,[23] who reported disagreement with some of the explanations previous to Ficken and Stephenson by observing flame maxima at pressure antinodes. Ficken and Stephenson responded[24] and suggested they may have been operating under "reversal" conditions, but since absolute static gas or acoustic pressures were not reported, it was difficult to tell. This indicates further the need for more quantitative experiments of the reversal phenomenon.

B. Examination of flame properties

A few years after the Ficken and Stephenson study, Spagna[25] examined the properties of the flames themselves during normal and reversal operation of the tube. Using a microphone and photocell, they observed that each flame was modulated at the drive frequency and consisted of a series of pulses (bright and dark bands) that traveled upward. Schlieren images of the flames showed that compression of the fuel jet produced dark regions of unburned fuel in the flame, which then burned from the outside in as the band traveled upward. A systematic correlation of phase between microphone and photocell was not observed for different flames, however. This suggested to the authors that the flames and the standing waves may be decoupled and the flame is only indirectly probing the acoustical field inside the pipe.

C. Inharmonicity of tube resonances

A recent study by Gardner *et al*.[3] centered on a phenomenon not previously described by the cited authors, who were understandably focused on the performance of the tube for each individual mode. The issue at hand was the inharmonicity of the lowest tube natural frequencies, which implies that the description of the tube in terms of simple boundary conditions, e.g., "closed-closed," is insufficient. If one assumes, as in Fig. 6, that the distance between flame heights is a half-wavelength (the distance between two nodes in an ideal pipe), then the calculated sound speed in propane based on $c = \lambda f$ appears to be highly dispersive, as shown in Fig. 7. This is not physically the case.

To investigate the reason for the inharmonicity of the resonance frequencies, an equivalent circuit model of the tube and boxed loudspeaker was constructed. The model-predicted and observed pressure amplitudes at the closed end of the tube are shown in Fig. 8 as a function of frequency. In both cases, the same shift in the natural frequencies from the harmonics predicted in the ideal closed-closed pipe. This shift can be attributed to two causes. First, the boxed loudspeaker affects the response of the lowest modes. Second, the presence of the holes themselves is important as they alter the input impedance, particularly at low frequencies. At higher frequencies, where the holes' acoustic impedance increases, the tube performance begins to approach that of the ideal closed tube with evenly spaced resonances.

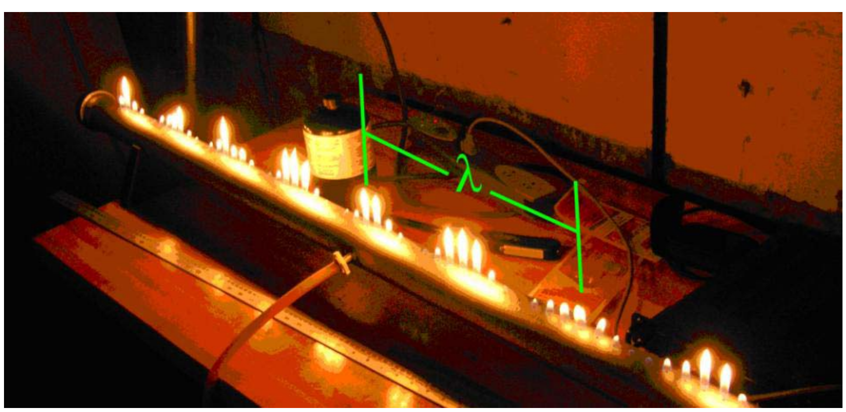

Figure 6. Example of how the flame tube apparatus may be used to calculate sound speed inside the tube. This approach assumes the distance between adjacent flame maxima corresponds to a half wavelength, which can be incorrect at low frequencies and lead to an apparently, highly dispersive sound speed calculation.

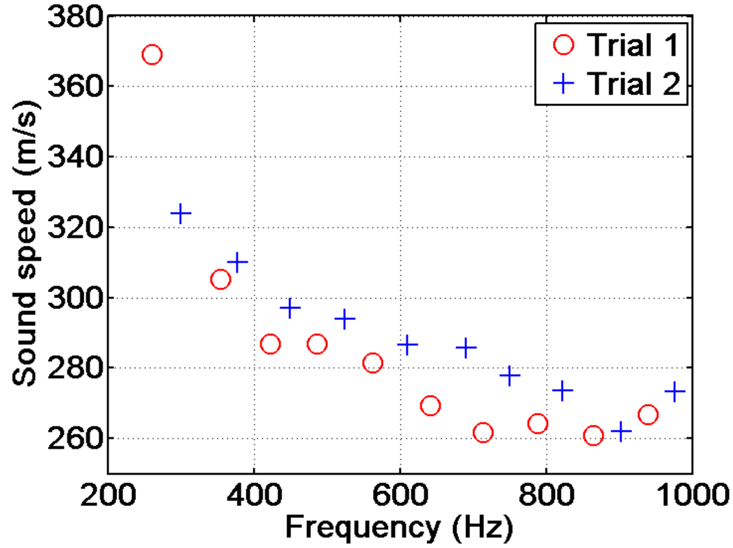

Figure 7. Sound speed calculated for heated gaseous propane when the distance between adjacent flame maxima is erroneously assumed to be a half wavelength (see Fig. 6).

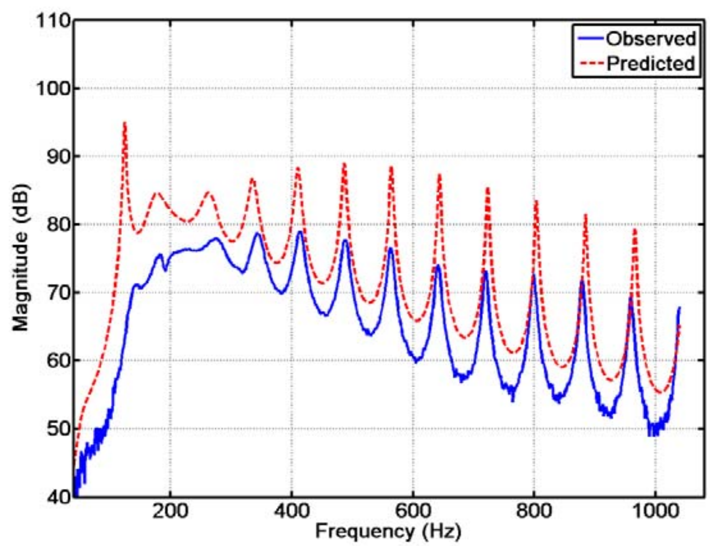

Figure 8. Modeled and measured spectral response at the end of the tube. Note the inharmonicity of the first several modes.

4. Conclusion

The Rubens tube captures the imagination and interest of the student and, consequently, has gained appreciable popularity during the past century. It can be used at a variety of academic levels to motivate discussion and promote understanding of the properties of sound waves. In moving forward, there are additional investigations that still deserve further attention. One is a better understanding of the reasons for the transition from normal to reversal operation of the tube and quantifying the roles of sound amplitude and gas static pressure in this process. Another is to build on the study of Spagna[25] to better understand the instantaneous and time-averaged nature of the flames as they relate to the properties of the sound field. In any case, this exciting demonstration will, in all likelihood, continue to motivate and engage physical science students for at least the next century.

Acknowledgments

The author thanks Dr. Scott Sommerfeldt for his help in understanding the articles written in German and Dr. Tracianne Neilsen for reviewing a draft of the manuscript.

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