

Henry Darcy's Perfection of the Pitot Tube

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Abstract

Starting in 1856 Henry Darcy, with the assistance of Henry Bazin, published four works that show various forms of an improved Pitot tube design. Although Henri Pitot had invented the device in 1732, theoretical and design weaknesses had kept it little more than a scientific toy. Darcy's improved instruments provided accurate and easy measurements of point velocity for the first time, which allowed advances in open channel and pipe flow hydraulics. His final design for the instrument tip is reflected today in all of our modern instruments. A reproduction of Darcy's published 1858 design was completed and shown to work as reported. Darcy's contribution to the development of the device equaled or exceeded Pitot's initial work, thus making it appropriate to refer to the modern instrument as the "Pitot-Darcy tube".

Introduction

The Pitot tube, is a simple and inexpensive instrument for the measurement of fluid velocity often taken for granted today. While largely replaced by rotating vane meters and various electronic instruments in hydraulic applications, it is still commonly used in pneumatic measurements and particularly for aviation airspeed determination. Its strength is of course its simple, robust design that allows an accurate velocity determination by measuring the pressure differential across two ports. While most practitioners appreciate the refinement of the instrument that occurred in the 20th century, many may not know its origin. This paper, which is a revised and expanded version of Brown (2001), will discuss the first instrument created by Henri Pitot, and the improvements made by Henry Darcy. In addition, basic testing is performed on a recreation of Darcy's design. It will be shown that Darcy, with the support of Henry Bazin, perfected the design into the useful instrument we use today.

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Pitot's Instrument

Henri de Pitot (1695-1771), a French engineer and an early member of the *Corps des Ponts et Chaussées* (Corps of Bridges and Roads), made contributions in several areas of engineering, math and science (Chevray, 1969). However, his 1732 paper "*Description d'une machine pour mesurer la vitesse des eaux courantes et le sillage des vaisseaux*" (Description of a machine to measure the speed of running waters and the wake of vessels) is the highlight of his remembrance. Pitot's instrument consisted of two glass tubes mounted vertically on a wooden frame that had a length scale attached. The static tube pointed straight down, while the Pitot tube had a 90-degree bend at the bottom to face the flow. To obtain a measurement, the instrument was lowered into the flow and the difference in the liquid level in the two tubes recorded (Figure 1). Pitot described his excitement with the invention by writing,

"The idea of this machine, known as a Pitot, is so simple and so natural that as soon as it had come to me, I ran at once to the river to carry out the first test with a simple tube of glass, and the effect met my expectation perfectly. After this first test, I could not imagine that such a simple, and at the same time very useful thing, had escaped so many skilled people who wrote and worked on the movement of water."

Pitot's device was recognized as innovative at the time and was described in detail by in the widely read thesis by Belidor (1737). However, it had four deficiencies that limited its application. First, Pitot did not provide the proper theoretical analysis for the device (Rouse and Ince, 1957). He equated the reading to the velocity attained by a falling body and prepared calibration tables of questionable accuracy. In fairness, while wrong his analysis was consistent with the practice of the day. Second, the instrument was slow and awkward to use. Third, the combination of the sizeable frame and the large static

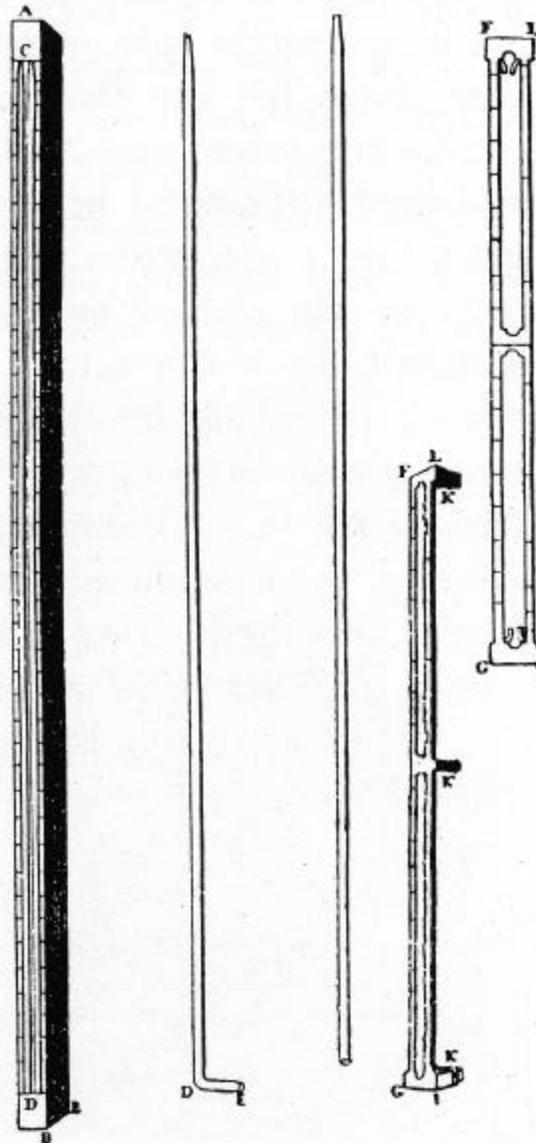


Figure 1. Henri Pitot's original design.
(Rouse and Ince, 1957,
reproduced by permission of IIHR.)

tube pointed downward distorted the flow and the precision of the static measurement. In fact, the water level in the static tube will in most cases be lower than the stream's water surface due to the fluid acceleration around its opening. Finally, all designs had trouble with oscillations in the water levels. There was no clear understanding of how the shape of the Pitot tube inlet affected performance. Some practitioners followed Pitot and used straight tubes, while others used tubes that had a funnel opening. An example of the latter is presented by Fanning (1877) (Figure 2). He writes, "The object of the expanded bulb and contraction below the bulb is to reduce oscillation of the water within the tube." The bulb obviously distorted flow around the device making its use problematic. Due to the instrument's weaknesses, it was little more than a scientific toy for the next 120 years (Hughes and Safford, 1926).

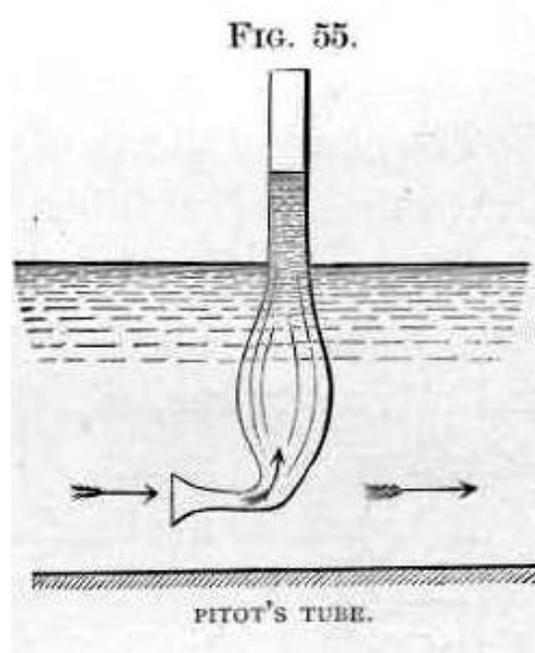


Figure 2. A funnel type Pitot tube
(Figure 55, Fanning, 1877)

Darcy's Modifications

In 1858 another member of the French Corps, Henry Philibert Gaspard Darcy (1803-1858), published a paper that revolutionized Pitot's instrument and brought it into large-scale use (Darcy, 1858). The paper, "*Note relative à quelques modifications à introduire dans le tube de Pitot*" ("*Note relating to some modifications to be introduced to the Pitot tube*"), was published just after Darcy's death (Figure 3a).

Darcy noted the four weaknesses of Pitot's instrument and proceeded to correct each. First, while he diplomatically ignored Pitot's theoretical shortcomings, he provided a somewhat inelegant, but correct, analysis of the instrument's reading based on Torricelli's equation. His final result was,

$$V = m\sqrt{2gh} \quad (1)$$

where V is the point velocity, g is the acceleration of gravity, h is the difference in the water levels and m is a calibration coefficient dependent on the tip geometry.

The analysis allowed the pressure at the top of the manometer tubes to differ from atmospheric, which justified his modification to address the second problem. The tops of both tubes were connected through a valve to a short mouthpiece. The operator could place a small vacuum on both by opening the valve, sucking on the mouthpiece and then closing the valve. The vacuum would draw the water up the tubes to a convenient height for reading, but since the pressure on both was equal, the difference would remain the same.

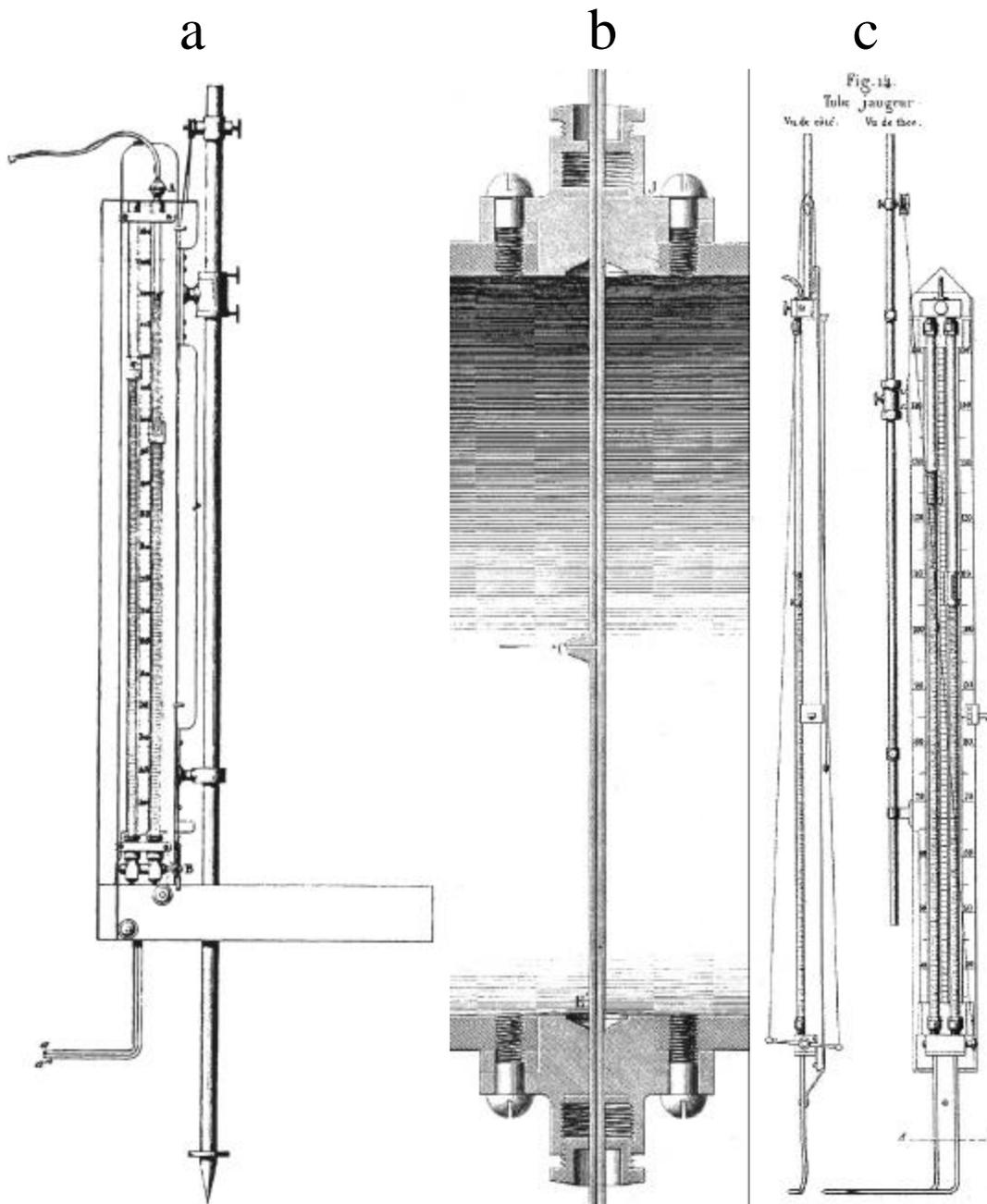


Figure 3. Darcy's Pitot tube designs by publication date;
a) 1858, b) 1857, c) 1856.

The third problem was addressed by replacing the bottom portion of the glass tubes with slender pipes that dropped clear of the support, and then bent forward. The Pitot tube of course faces the flow, while the static tube opened to the side. In addition, the tube support was tapered on both the leading and trailing edges. With these modifications in place Darcy stated, "Thus it is seen that the water is only very-imperceptibly disturbed at the point where the velocity is measured." Finally, his solution for the oscillation problem required two steps. He wrote,

"Then I made the oscillations in the tubes disappear almost entirely by making the openings only one and a half millimeters in diameter, while that of the tubes was one centimeter. As these oscillations, however reduced they were, could still confuse the operator; I placed a valve so that one can simultaneously close the lower openings of the tubes; these openings being closed, any communication with the current is stopped, and one can read the difference to deduce the velocity with ease and precision."

This paper was neither the first nor last of Darcy's publications that addressed the use of Pitot tubes. A comparison between these publications shows a steady advance in instrument design. Darcy's first use of the device (Darcy, 1857; Gisonni, 2003) was in the measurement of the pipe flow velocity distributions. (The actual work was done from 1850 to 1854.) Figure 3b shows the Pitot tube that he installed in pipe test sections. The tube could slide up and down and fit into a recess in the pipe wall, while the static line was installed flush on the pipe wall. This device displays a tapered tip and valves to stabilize the readings consistent with the later designs. It is quite possible that the valves were installed for operational reasons, and their use in measurement came later. Darcy (1856) shows a very similar design to the 1858, with the exception of the tip. In Figure 3c, the string and pulley apparatus that allows both lower valves to be closed simultaneously from above can be seen. The last publication, (Darcy and Bazin, 1865; Hager and Gisonni, 2003) again showed a design similar to the 1858 device with a third tip design. Henry-Emile Bazin (1829-1917) was Darcy's protégé and assisted him for several years, and Darcy acknowledged his work on the testing of the Pitot tube (Darcy, 1858). The 1865 publication presented the results of open channel experiments originally designed by Darcy, but Bazin undoubtedly wrote the entire document.

Figure 4 presents the three instrument tip variations. The 1856 drawing shows the Pitot tube lengthened considerably compared to the pipe-flow device (Figure 4a). More importantly, the static line was placed next to the Pitot line, and its opening formed by a sideways 90° bend. In 1858, the static pressure line opens with what appears to be a soldered fitting mounted on the bottom, but its details are neither clear in the text nor in the illustration (Figure 4b). Finally, the 1865 report presents a streamlined assembly very similar to modern designs (Figure 4c). However, the publication dates of the three tip designs are probably misleading, as to when they were actually in service. Darcy (1856) describes three calibration tests with different static port designs, and in a footnote, Darcy (1858) seems to describe the 4b design as a fabrication error, which he replaced quickly with 4a. Similarly, in the discussion of calibration coefficients, he states the 4a design has a calibration coefficient, $m = 0.84$, while another tip with the static port formed by simply piercing the tube wall had a coefficient of 1. Only a design similar to 4c could have had a coefficient with that

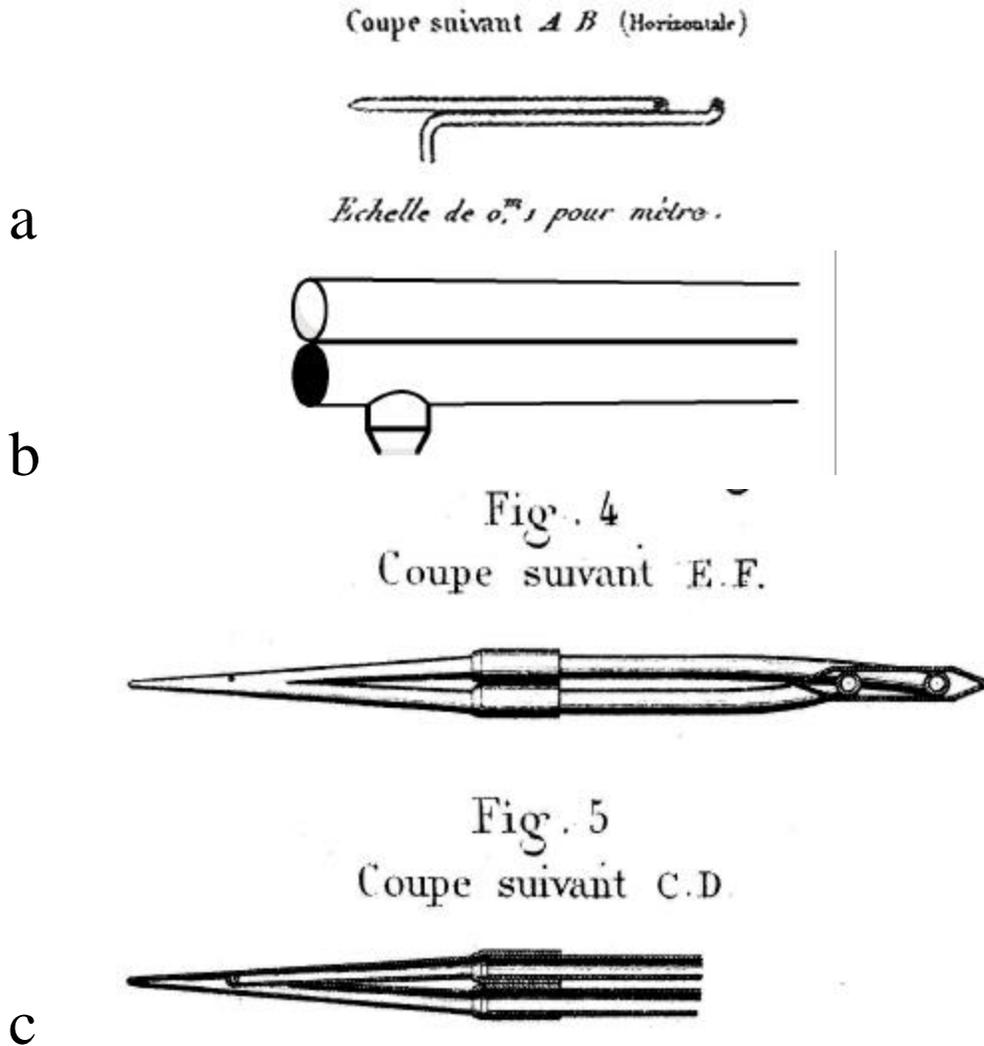


Figure 4. Darcy's tip designs by year of publication;
a) 1856, b) 1858, c) 1865. (Figure 4b by author.)

value. Since the 1858 paper was published after his death, it is possible that the drawing of the older instrument was used by the editors, instead of the most recent design.

When closing the topic, Darcy (1856) wrote the rather prophetic statement; "It is essential to notice that a seemingly unimportant modification in the form or the provision of the second [static] tube can have a great influence on the value of m' ". This fact of course leads to a variety of subtle design modifications through the years (Peters, 1931), with the best generally credited to Ludwig Prandtl (1875-1953) (Merriam and Spaulding, 1935). His design called for a rounded tip Pitot tube to project 11 to 13 tube diameters ahead of the tubing bend, and the static port to be a continuous ring, three tube diameters behind the Pitot port. As can be seen, the tip shown in Figure 4c approaches that design.

Instrument Replica

In an effort to gain a better understanding of Darcy's design, a replicate of the 1858 instrument was constructed (Figure 5). If the 1858 paper did not provide design guidance for a given feature, the other reports were consulted. In the end, several details had to be inferred, but it is believed that the result is a fairly truthful model. An initial difficulty was in maintaining a period look with modern materials. In particular, the lower valves were troublesome to duplicate. No stock designs could be located that would allowed two valves to be operated by a single level. As a result, it was necessary to rework two old brass stopcocks into a single assembly. The final instrument was 191 cm tall, 47 cm deep across the rudder and 4 cm wide at the manometer board. The extensive use of brass fittings and a steel pipe (2.1 cm OD, 1.6 cm ID) produced a relatively hefty 6.0 kg apparatus.

Figure 6 shows the device in a flume with a water velocity of 0.3 m/s. As can be seen, the design was effective in minimizing flow disturbance. Rather humbling for the author was the difficulty encountered in getting the vacuum differential to work properly. *Any* leak in the system would result in erroneous readings. Thus, all fittings and connections had to be tight fitting, but resilient to operational shocks, which proved to be difficult to achieve. The glass manometer tubes broke more than once, and their rigid connection to the lower valve had to be replaced with flexible shrink tubing. Likewise, the lower brass stopcocks had to be replaced with very un-period looking modern valves before the instrument would work properly. Once



Figure 5. Replica of 1856 Pitot-Darcy tube.

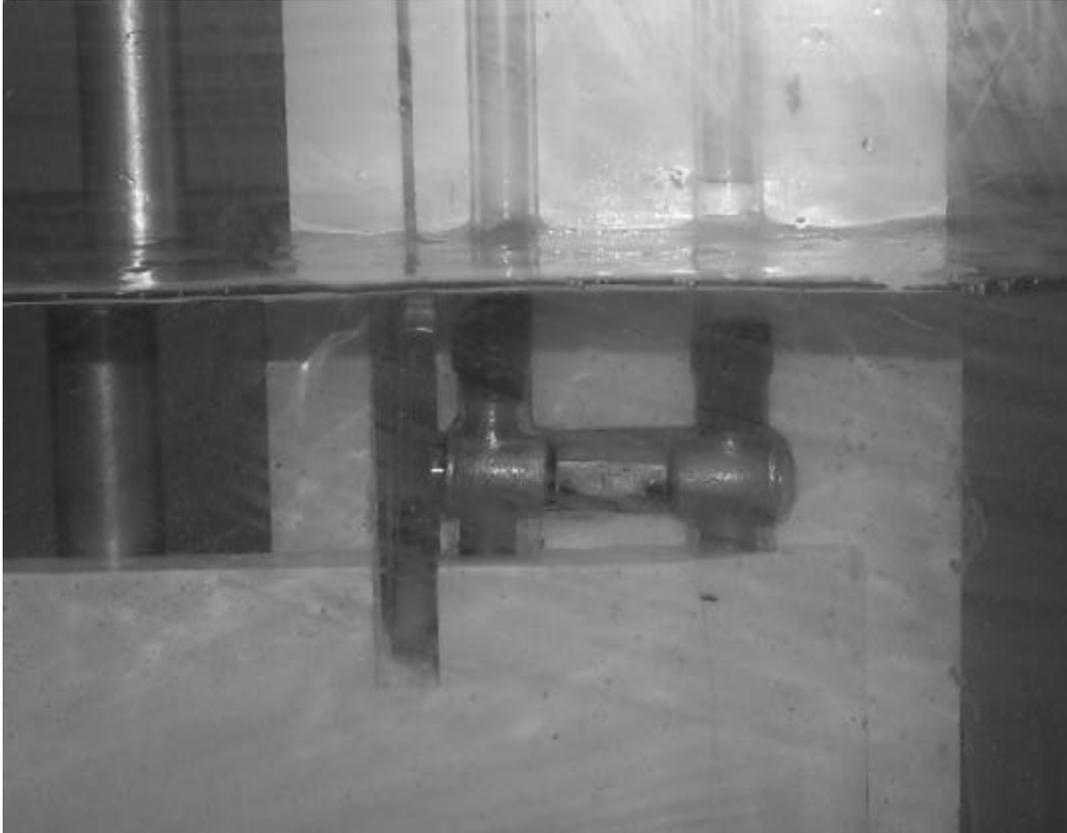


Figure 6. Replica of 1858 design in testing.

everything was tight, it worked well and the calibration obtained was similar to that reported by Darcy. Overall, the experience impressed upon the author the obvious skill of the 19th-century instrument makers who made the original.

Concluding Remarks

Darcy's improvement of the Pitot tube was soon put to work by other researchers and contributed to the rapid advances in hydraulics of the late 19th and early 20th century. An example of data being collected with the 1865 design is presented in Figure 7 (Darcy and Bazin, 1865), while Figure 8 shows Bazin's plotting of the isovels obtained in a rectangular channel. Integration over the area allowed accurate estimates of volumetric flow and channel resistance. Similar detailed analysis of pipe flow isovels (Darcy, 1857) allowed improvement in close conduit friction equations.



Figure 7. Technicians using a Pitot-Darcy tube (Darcy and Bazin, 1865).

Finally, it should be noted that Darcy unselfishly gave the instrument to the world. Charié-Marsaines (1858) wrote,

"Perfections brought by Darcy to this instrument are considerable and he would have been able to take a patent to profit from its exclusive manufacture during a certain number of years. However, as a believer in the customs of disinterestedness, he decided to abandon his invention to the public. The administration has already made a number of these instruments some of which are placed in the precision instrument deposit at *l'École des Ponts et Chaussées*, and others sent to state engineers to be used in operations that demand exact measurements of the water velocity."

Clearly, Darcy's contribution to the development of the device equaled or exceeded Pitot's initial work. Thus it is only right, as some authors do now, to refer to the modern instrument as the "Pitot-Darcy tube". With this nomenclature, the dynamic pressure is measured with the "Pitot" tube, while the hydrostatic pressure is obtained with the "Darcy" tube.



Figure 8. Example of open channel isovels from Darcy and Bazin (1865).

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