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Maurice Couette, one of the founders of rheology

J.M. Piau[1], M. Bremond[2], J.M. Couette[3] and M. Piau[1]

[1]Université de Grenoble (UJF and INPG), Laboratoire de Rhéologie, Grenoble, France
[2]Université Catholique de l'Ouest, IRFA, Laboratoire de Physique, Angers, France
[3]3, place Raoul II, 35133 Landean, France

Abstract: This article presents a biography of Maurice Couette, whose name is associated with a type of flow, of viscometer, and with a correction method for end effects in capillary flows. His life and work are described, with special mention being made of the cylinder apparatus that he designed. The relevance of his work to present day rheology is stressed.

Key words: Couette – biography – viscometer – Couette cells, flow and corrections – rheology – adherence

1. Introduction

The name of *Couette*, the French physicist, is associated today by any student of fluid mechanics with a type of flow created between two tangentially mobile walls, or with a measurement cell in which the fluid is placed between two concentric cylinders. Maurice Couette was also the discoverer of a correction method and factor that govern entrance effects in Poiseuille-type flows. However, the impact of his work on the choice of boundary conditions for fluid adherence at the wall has not been sufficiently emphasized. Furthermore, little is known about the man himself, apart from his remarkable work on the study of liquid viscosity published at the end of the last century in Paris.

This article is an attempt to present as complete a biography as possible of Maurice Couette. Chapters 2 and 3 deal with his life and the writings he left, and contain a large amount of information hitherto unpublished. His main works in the field of fluid mechanics are then discussed in chapter 4 and the cylinder apparatus he constructed to measure the viscosity of liquids is described in chapter 5. These two chapters underline the quality, originality and precursory nature of the research carried out by Maurice Couette in this field.

Lastly, chapter 6 looks at recent developments concerning Couette cells, flow and corrections, thus stressing the many modern spin-offs from his work in rheology.

2. His life

2.1 Youth

Maurice Marie Alfred Couette, was born on January 9, 1858, at Tours on the river Loire in the west of France. He died on August 18, 1943, at Angers. Maurice Couette's father, Alfred Ernest Couette, was born at Tours in 1825. He was a cloth merchant, specializing in white cotton goods, whose business was located at 15 rue de l'Intendance, Tours. In February 1857 he married Marie Adélaïde Françoise *Leduc*. Maurice Couette was an only son. Educated by the Frères des Ecoles Chrétiennes in Tours, he passed his baccalaureate in humanities in July 1874 and in sciences in September of the same year, receiving his diplomas from the Poitiers district education authority.

After taking an advanced course in mathematics at Tours grammar school in 1876, he went on to obtain a bachelor's degree in mathematics in December 1877 from the Faculty of Sciences of Poitiers. Maurice Couette then enrolled at the newly opened Free Faculty of Sciences in Angers in January 1878 and prepared there for a degree in physics that he received in July 1879, also from Poitiers. From January 1879 to February 1880 he gave courses in elementary mathematics in conjunction with the Free Faculty of Sciences.

In 1880, he joined the 12th Artillery Regiment at Vincennes, near Paris, where he completed one year's voluntary military service. He then rose in the ranks of the reserves, becoming a sub-lieutenant in 1884 and a lieutenant in 1892.

2.2 The Parisian period

After completing his military service in 1881, Maurice Couette settled in Paris[1]). He gave maths lessons at home. He enrolled in the physics laboratories at the Sorbonne and then attended lectures in physical sciences (1881 – 1883) preparing for the *agrégation* (an advanced teaching diploma). At the same time, he acted as examiner at the Collège Stanislas. From 1883 to 1887, he continued working at the Collège Stanislas and at the same time began teaching physics at the Ecole Albert-le-Grand at Arcueil outside Paris, and in 1884 at the Ecole Sainte-Geneviève, 18 rue Lhomond, Paris. He was also a member of the Cercle Catholique du Luxembourg and Patronage de Sainte-Rosalie in the 13th district of Paris.

It was at this time that he met Jeanne Lucile Anna *Jenny*, 7 years his junior and the eldest of four children. Her father, Auguste Jenny, was a native of Sélestat. A cavalry officer in the Imperial Guard, he had become a major in the 10th battalion of the Seine militia and died in combat at Stains in December 1870. Jeanne Jenny had thus become a war orphan and was well-educated at the Maison de la Légion d'Honneur in Saint-Denis near Paris. Maurice Couette and Jeanne Jenny were legally married on August 3, 1886 at the town hall of the 6th district in Paris, and the church service took place the next day in the church of Saint-Sulpice.

The Couettes lived a very hard-working life, governed by the religious principles instilled in them during their youth. Maurice Couette's wife bore him eight children, five boys and three girls, one of whom died in childhood. The eldest, Joseph, born in 1887, and the youngest, Paul, died before reaching the age of 20. One of the girls, Geneviève, who became a nun, followed in her father's footsteps after going through university and taught humanities. Over the years, 21 grandchildren were born, to the delight of their grandparents.

From 1887 onwards, Maurice Couette studied at the Physical Research Laboratory at the Sorbonne, while continuing his examiner's activities at the Collège Stanislas and Ecole Sainte-Geneviève. He prepared a thesis under the supervision of Gabriel Lippmann. In 1883, Lippmann had replaced Charles Briot (whose work on light scattering is well known) in the chair of mathematical physics and upon the death of Jules Jamin in 1886 was appointed to succeed him in the chair of experimental physics that he occupied at the Sorbonne. Elected to the Academy of Sciences in 1886, Lippmann did his early research into electrical and capillary phenomena. He was awarded the Nobel Prize in Physics in 1908 "for his method, based on the interference phenomenon, for reproducing colours photographically" (discovered in 1881).

Maurice Couette was also privileged to study under Joseph Boussinesq, the largely self-taught French mathematician, whose work dealt with many aspects of mechanics, especially hydraulics and the strength of materials. Boussinesq was elected to the Academy of Sciences in 1886, and in the same year appointed to the chair of physical mechanics at the Sorbonne.

Maurice Couette completed his doctoral thesis on the "Studies on liquid friction" at the beginning of 1889, and the final version was handed over to Gabriel Lippmann at the end of May 1889. This thesis was officially registered at the secretariat of the Faculty of Sciences of Paris on October 18, 1889. The authorization to print the thesis was given on March 20, 1890. Maurice Couette defended his thesis on May 30, 1890 and was awarded his doctorate in physical sciences at the Sorbonne "with all white balls"[2]) and *cum laude.*

Maurice Couette then opened a private secondary schooling establishment at his home at 6 rue de Mézières in Paris on February 25, 1890. This was attended by external students preparing their baccalaureates in the arts and sciences. Official authorization to do this was obtained from the Paris Education Authority.

2.3 The Angers period

It was shortly after this that there came a major turning point in Maurice Couette's career. He was asked by Monsignor Freppel, the Chancellor of the Catholic University of Angers (now known as the UCO) to come and lecture there. The pay was hardly enticing as the UCO, which had been created in 1875, was in a precarious position. However, Maurice Couette had been anxiously awaiting an offer of this kind and felt that it was his duty to respond to so flattering an invitation. He was strongly encouraged in this decision by his wife Jeanne.

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[1]) He lived successively at 61 rue Madame, 140 boulevard d'Enfer (now boulevard Raspail), and 6 rue de Mézières after his marriage.

[2]) i.e., unanimously, as each member of the examining board had a white ball and a black one to signify approval or disapproval.

So, on September 23, 1890, he closed his establishment in Paris and left for Angers, where he was to spend the next 43 years as Professor of Physical Sciences at the Free Faculty of Sciences. He lectured in particular in mechanics, electricity, optics, thermodynamics, and a little later began teaching physics and meteorology at the Catholic University's School of Agriculture, set up in 1898. He also gave courses at the School of Commerce and Externat Saint-Maurille during the First World War and subsequently at the Ecole Freppel, a private secondary school for girls.

From this date onwards, his scientific activity was extremely varied, in spite of the limited facilities at his disposal in Angers and the intense teaching activity he had to pursue in order to meet his family's needs. Indeed, there was growing conflict within France at the time and this eventually led to the official separation of Church and State in 1905. Maurice Couette contributed to a number of anthologies, writing articles on both theories and experimental research. Examples included osmosis theory in batteries or sound propagation phenomena.

In particular, he supervised the doctoral research of Fernand Charron at Angers. His thesis, entitled "The influence of air in friction between solids", was presented in Paris in 1911, and Fernand Charron was later to succeed Maurice Couette as Professor of Physical Sciences at the UCO. Maurice Couette also wrote a number of scientific articles and analyses for the journal La Science Catholique. The Catholic Faculties had in fact asked him to take charge of the Physics Bulletin for this journal.

Maurice Couette had been elected a member of the French Physics Society in 1888. At the time of his departure for Angers in 1890 he became a non-resident member and kept this status for many years. As a Professor at the Catholic Faculties, he kept in contact, at least for a certain time, with university research being carried out in physics in Paris, as borne out by the analysis of an article he published in the Journal de Physique in 1901 and his election in 1907 to the Council of the French Physics Society for a period of 3 years.

Recognition from the Catholic community of his eminent services rendered to Catholic higher education and for his exemplary lifestyle led to Maurice Couette's being appointed a Knight of the Order of St. Gregory the Great by Pope Pius XI in 1925.

He gave up his university teaching in 1933 and died 10 years later, 2 years after his wife, loved by all those close to him and a figure of great esteem. On the golden wedding anniversary of Maurice and Jeanne Couette in August 1936, which was celebrated at St. Thomas Aquinas in Angers, a homily praising their exemplary lifestyle and great merits was delivered by Monsignor Costes, Bishop of Telmesse and coadjutor to the Bishop of Angers, a personal friend. Figure 1 shows Maurice Couette at this period. His funeral was attended by more than 300 local and regional dignitaries in addition to his family and close friends.

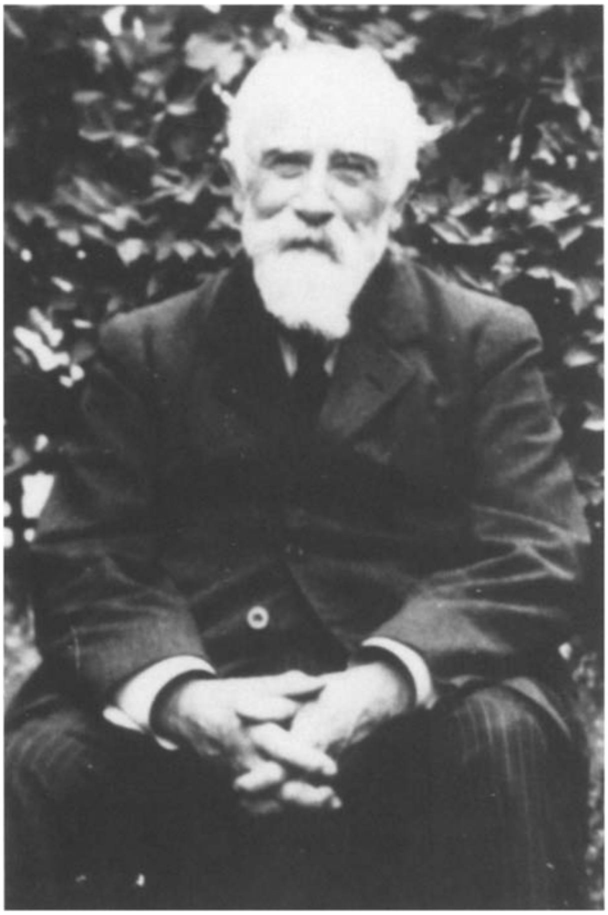

Fig. 1. Maurice Couette (1858 – 1943)

The scientific community in France and world-wide has adopted Couette's name to describe a type of flow between two walls moving tangentially to one another, and also for the cell that he built and the correction factors he calculated. But still, little is known about the professor, researcher, and extremely cultivated man of science that he was throughout his life.

3. His writings

The writings of Maurice Couette (see Appendix) are generally little known. Apart from his thesis and its published version in the Annales de Chimie et Physique in 1890, the most often-quoted are a note in the Comptes Rendus à l'Académie des Sciences in 1888, and an article in three parts in the Bulletin des Sciences Physiques on the viscosity of liquids. As these are often quoted in an abbreviated form (Guyon et al., 1990), and the same errors are carried over from one list of references to another, there is every reason for going back to the original texts.

His first publication was in fact in the Comptes Rendus des Séances de l'Académie (1887). This was the abstract of a research report, presented to the Academy of Sciences by Henri Poincaré, in which Maurice Couette sketched out a theory of the "rotating oscillations of a revolving solid in contact with a viscous fluid". In this, he announced the experiments undertaken at Gabriel Lippmann's laboratory. This report was not included in the "Mémoires des Savants Etrangers" as it was withdrawn from the Academy's secretariat in 1888 by the author himself. Maurice Couette gave an improved version of it in chapter IV of his thesis.

At the beginning of 1889, as part of the preparatory work on his thesis, he gave several oral presentations at the two-monthly sessions of the French Physics Society (SFP), which were summarized in the Society's Bulletin. He also presented an apparatus at the 1889 Universal Exhibition in Paris. Two articles were published in the Journal de Physique in 1890. On April 8 – 9, 1890, Maurice Couette also gave a public presentation of the cylinder apparatus that he had built to measure friction in liquids, at a special annual session organized by the French Physics Society for original scientific equipment.

The topic suggested to him by the Faculty as a second thesis subject concerned chemical reactions produced by electricity. The report corresponding to this work has not come down to us, but the article on the constancy of the electrochemical equivalent that he published in 1892 in the Journal de Physique shows his ability to make interesting contributions to this subject, which was new to him. A little later, he worked on the osmosis theory of batteries, in relation with the theory developed by Walter Nernst, and the various articles he published in the Journal de Physique in 1900 show his mastery of this subject as well.

From 1893 to 1900, Maurice Couette made regular contributions to the journal La Science Catholique, in which he analyzed and commented on publications and recent advances in many fields of physics. There were also more personal areas of research, such as, for example, that discussed in his paper concerning the reflection and refraction of sound, delivered at the 1895 Scientific Congress in Angers and published in the Proceedings of that congress, along with a few articles of a pedagogic nature.

Maurice Couette thus left many writings, but sadly, these were not widely circulated and are even less accessible now. Nevertheless, they give the reader an idea of his scientific approach and the openness of mind that was so typical of him.

4. His work in the field of fluid mechanics

The subject dealt with by Maurice Couette in his thesis followed on the famous research of Navier (1823). In 1822, Navier had established equations expressing the movement of a fluid while taking into account friction. Couette's work studied the coefficient of internal friction of liquids (which was not yet referred to as viscosity). The best way of situating Maurice Couette's work is to reproduce the summary contained in the French Physics Society's Bulletin of the oral presentation he delivered on March 1, 1889:

> "Mr. Couette has subjected the equations put forward by Navier to new experimental verification, in order to represent the movement of liquids while taking into account their viscosity. He has used two methods and worked with water.
>
> Firstly, the liquid is confined between two concentric cylinders: the outer cylinder rotates with a uniform movement, while the inner one is held immobile by weights, with which it is possible to measure the friction moment M of the liquid against the cylinder. The dimensions of the apparatus are:
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> | | |
> |---|---|
> | Radius of the outer cylinder: | 14.6395 cm |
> | Radius of the inner cylinder: | 14.3942 cm |
> | Height of the inner cylinder: | 7.905 cm |
>
> When the number of rotations N of the outer cylinder is less than 56 per minute, the ratio M/N maintains a constant value, which is in conformity with the simplest particular integral of the Navier equations. Between 56 and 60 rpm, this ratio experiences an extremely rapid increase, which then slows down. Above 127 rpm and up to 150 rpm, which was the experimental limit, M/N was approximately a linear function of N.
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> Secondly, the water flows in glass tubes with a diameter of between 0.1 and 1 cm. The influence of the extremities is cancelled by a process similar to that of Wertheim for sound tubes. If q is the flow rate and i the head loss per unit length, then while the flow rate remains below a certain limit q_1, which is proportional to the radius of the tube, flow obeys Poiseuille's laws; when q varies from q_1 to a

certain limit q_2, the ratio i/q increases rapidly; beyond q_2, the ratio i/q is approximately a linear function of q.

Observation of the jet of liquid streaming from a horizontal tube also throws an interesting light on these results. When the flow rate is below q_1, the jet is smooth and undisturbed; when it is above q_2, it is again undisturbed, but when it is between q_1 and q_2, there are sudden changes in the appearance and amplitude of the jet, which follow one another rapidly at irregular intervals; the jet is alternately smooth and elongated or rippled and shortened.

This experiment was repeated quite clearly in front of the members of the Society, using a jet of mercury, while an enlarged image was projected on to a screen.

Conclusions – The movement of liquids has two different regimes. The first, which occurs alone in the slowest movements, is represented *exactly and not approximately* by the simplest particular integrals of the Navier equations. The second, which occurs in more rapid movements, does not comply with these integrals. When the velocities are between certain limits, the two regimes are possible and occur alternately".

Maurice Couette thus used two experimental approaches:

- The first made use of the ideas expressed by his forerunners: G.G. Stokes in 1845 (published in 1849), and Max Margules (1881), who proposed to reproduce flow between two concentric cylinders rotating at different speeds. This approach led to the construction of the viscometer that will be discussed further on.

Maurice Couette performed the theoretical calculations associated with this approach with the greatest care, making sure to take into account interference effects (such as poor coaxiality and end effects).

- The second used measurements of head loss during flow in fine tubes, a configuration used earlier by Poiseuille (1846). Maurice Couette clearly demonstrated that head loss was proportional to the length of the tubes during steady fully developed regimes, and that there was zero velocity at the wall for the various fluids and wall materials used.

For both of these experimental set-ups, Couette discussed the range of velocities for which the relations established for laminar flow no longer held true, thus demonstrating the existence of a different regime that in fact corresponds to the transition from laminar to turbulent flow. Maurice Couette only learned of the article by Osborne Reynolds (1883) after he had completed his thesis work, and therefore does not explain the reasons for this change in regime, as one might expect. In contrast, his work has the advantage of linking flows in tubes studied by Poiseuille and traditional hydraulics.

Maurice Couette also carefully established equations for the movements involved in the flow configurations he used, and accurately evaluated the errors committed during previous experiments or possibly occurring during his own. He also performed the difficult calculations for movements in a fluid close to the wall during the slow rotating oscillations of a revolving body.

The main merit of Maurice Couette, which was indeed recognized by his contemporaries and, in particular, the examiners of his thesis, was the meticulousness and skill with which he carried out theoretical calculations. Combined with great powers of observation and imagination in his experimental approach, these qualities enabled him to produce results in his thesis that have become standard references. "Couette movements" were quoted as such in scientific works right at the beginning of this century. An example is the "Lessons on the viscosity of liquids and gases" by Marcel Brillouin, published in Paris by Gauthier-Villars in 1907.

The results that struck Joseph Boussinesq and Gabriel Lippmann concerned his repeats of the experiments carried out by Poiseuille using fine tubes. Gabriel Lippmann had the clear-sightedness to consider that Couette did not sufficiently stress the absence of slip at the wall that he had observed in his experiments, in which he used tubes made of glass (clean, greased, varnished and silver-coated), copper, white metal and paraffin.

One of the consequences of this is that the studies on rotating flows begun by Maurice Couette at the Physical Research Laboratory were not continued after his departure. Gabriel Lippmann's interest laid more with electrical and thermodynamic phenomena while Joseph Boussinesq, whose contribution to the work of Maurice Couette is attested to by the author himself (Boussinesq (1877) is often quoted in Couette's thesis) studied a wide range of subjects in theoretical hydraulics.

5. The Couette viscometer

When he left the Sorbonne for the Catholic University at Angers – a choice guided by his personal con-

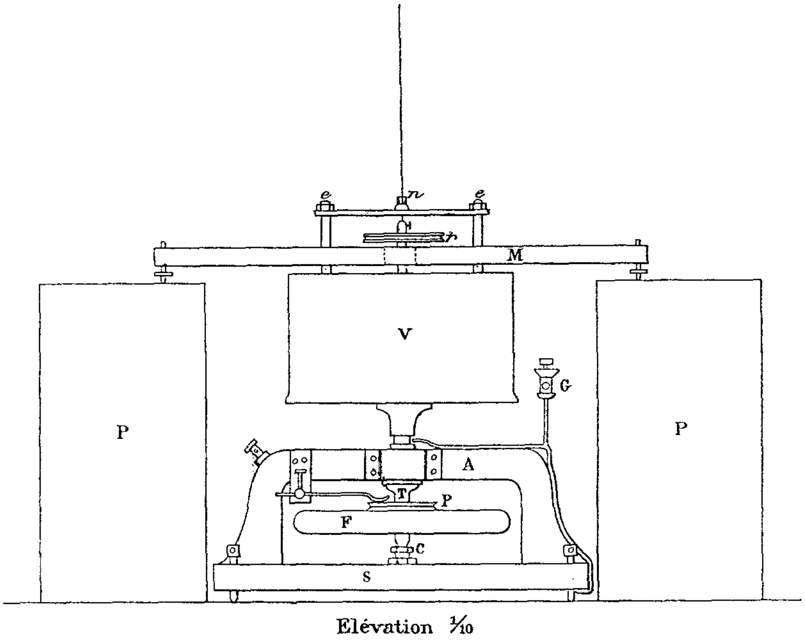

Fig. 2. Diagram of Couette's apparatus (front-view), taken from Fig. 2, p. 16 of his thesis

victions – Maurice Couette took with him the cylinder apparatus that he had used to carry out the viscosity measurements described in the first chapter of his thesis. For many years, the dismantled apparatus laid unused in a store-room, unknown to most people. It was brought out and refurbished by Michel Brémond and Maurice Dubois, professor and honorary professor of physics at the UCO, on the occasion of an exhibition of old instruments organized by this university to mark the beginning of the 1990 – 1991 academic year.

Two years later, on May 12 – 15, 1993, an international congress was held at St. Lazare priory at the Royal Abbey of Fontevraud, on the subject of polymer rheometry. The congress was supported by the EEC and the Proceedings are to be published in the JNNFM. Jean-Michel Piau, who organized the congress, wished to gather as much information about Maurice Couette (who was from that region) as possible. With valuable assistance from these professors, it was possible to retrace Maurice Couette's career, and his apparatus was shown to the participants, including university research workers and industrialists from many countries, 50 years after its inventor's death and more than 100 years after it was built.

Figures 2, 3, and 4 are exact reproductions of the original diagrams for the apparatus presented in Maurice Couette's thesis on pages 16, 17, and 18 (and in volume 21 of the Annales de Chimie et Physique (1890), on pages 446 – 447). They indicate the respective arrangement of the inner measuring cylinder *s*, which is centered and held in position during rotation by devices *C'* and *n* and fixed guard rings *g* and *g'*, and of the outer rotating cylinder *V*. The cross-section (Fig. 4) was redrawn in two articles (Donnelly, 1991, 1992) describing the history of Couette-Taylor instabilities³), but was unfortunately represented as being symmetrical, which meant that two screws had to be introduced to hold the rod *h*, instead of the single

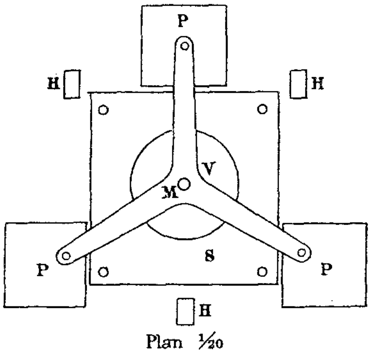

Fig. 3. Diagram of Couette's apparatus (plan-view), taken from Fig. 3, p. 17 of his thesis

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³) These two review papers by R. J. Donnelly contain a short abstract of Couette's work on the cylinder apparatus. The bibliographical summaries are concerned with the problems of stability in flows. Taylor's study dealt with Newtonian flows. These articles therefore give only a partial view of Couette's work, overlooking his fundamental contribution.

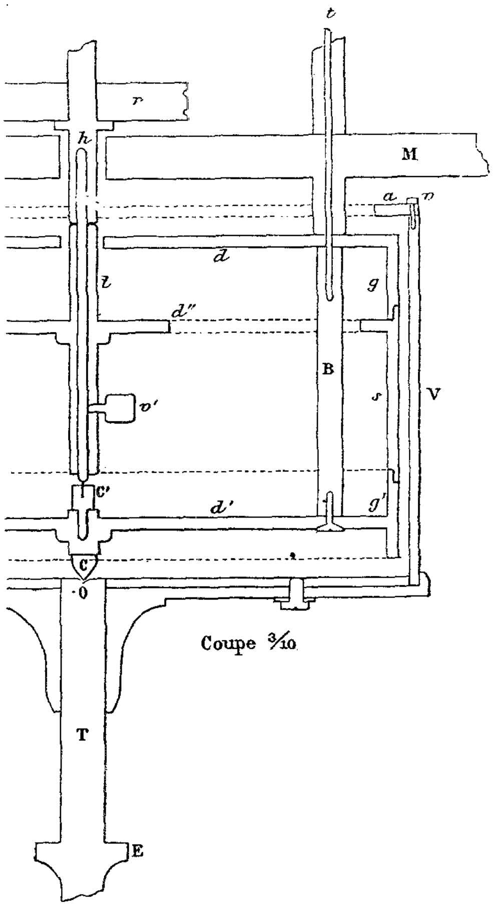

Fig. 4. Cross-section of Couette's apparatus, taken from Fig. 4, p. 18 of his thesis

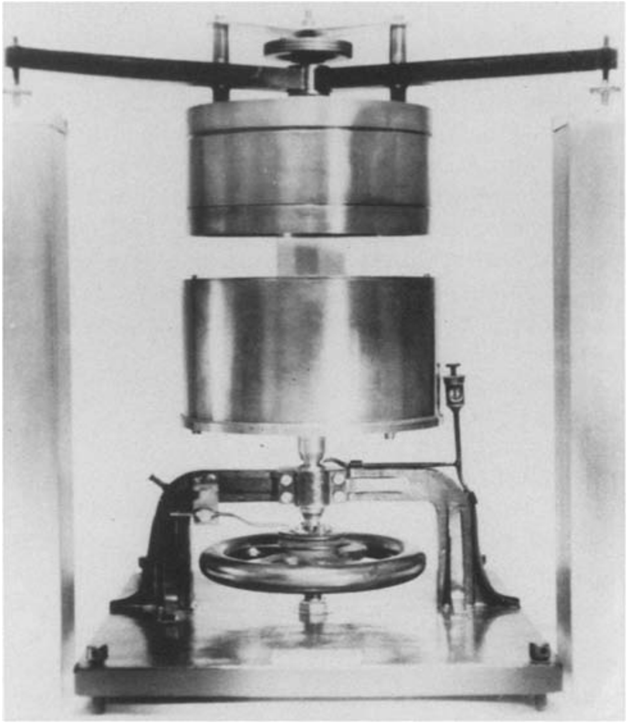

Fig. 5. The cylinder apparatus (viscometer) of M. Couette (1888)

screw v'. Figure 5 shows the original apparatus in its present state, with the inner cylinder-guard rings assembly having been taken out of the rotating cylinder for the photograph.

The apparatus was built by Eugène Ducretet, a remarkable Parisian maker of precision instruments for laboratories and industry. Eugène Ducretet held many patents, and throughout his life, which was devoted to scientific and technical progress, he built many devices that incorporated the latest discoveries of his period in the fields of physics and chemistry (electricity, thermodynamics, radiology, etc.) while at the same time making a number of genuine inventions in a variety of areas. In particular, he built the first wireless telegraph sets to operate on land in 1898. The firm of Ducretet, which kept the name of its founder after his death in 1908, joined with Thomson-Houston in 1931 and built, among others, the Ducretet-Thomson radio receivers.

The clever and meticulous design of Couette's cylinder apparatus and the various ingenious devices it incorporates, such as the guard rings, the Atwood machine pulleys that replace the torsion wire for measuring high torques, the inertia flywheel, lubricated bearings, centering systems that oppose whirl instability and resist the dynamic unbalances of the rotating parts, the electrical drive and velocity measuring systems are all original features and definitely contribute to the accuracy and reliability of the measurements obtained. Theodore Schwedoff, Dean of the Faculty of Sciences of Odessa, wrote to Maurice Couette on February 21, 1889, to thank him for sending a copy of his work, and he emphasized the care that was needed in order to avoid errors in the experimental method.

At the time Maurice Couette was beginning the construction of his apparatus and carrying out his first measurements, a young British researcher, Arnulph Mallock, who was the nephew of William Froude, joined Lord Rayleigh's laboratory. He began building a similar type of cylinder apparatus, with a system that enabled either of the cylinders to be rotated. His first measurements were presented by Lord Rayleigh in November 1888 at the Royal Society (Mallock, 1888), as having been obtained in April-May of that same year. They underwent a few corrections before being published in their final version of the Proceedings.

In the text of his thesis, Maurice Couette referred to these first British tests. He analyzed the problems of out of balance and end effects that had not been taken into account in the design of the apparatus. Seven years later, Arnulph Mallock published a more complete article (Mallock, 1895), in which he described the measurements carried out between 1893 and 1895, and alluded to various interference effects that might affect the accuracy of the viscosity measurements.

A further analysis of Mallock's apparatus was carried out by G.I. Taylor (1923). The possible sources of error in the experimental set-up, ranging from the dimensions chosen for the cylinders and the gap, to the influence of the type of bottom and suspension method, are all described. These errors are all the more serious when the inner cylinder is the one that moves.

Maurice Couette's apparatus was used to carry out measurements on water, oils and, even more surprisingly, air. His results appear to be worthy of confidence, and the theoretical developments he made add to the value of his work.

6. Developments and spin-offs from the work of Maurice Couette

6.1 Couette cells

Maurice Couette's cylinder apparatus is an exemplary instrument. Right up to the present time, is has continued to be a constant source of inspiration for many devices that make similar use of rotating (outer and inner) cylinders, but which differ considerably in detail. These are commonly referred to as "Couette cells". It is impossible to describe these exhaustively, as the field is so wide.

Generally speaking, guard rings of the type used by Maurice Couette are no longer included, while the desire to build instruments that give an absolute measurement has given way to the use of highly effective instruments that give a relative measurement of mechanical properties. Sometimes, inner cylinders with a conical end are used to reduce end effects and bell-shaped inner cylinders improve sensitivity at low viscosity levels. When there is too large a gap between the cylinders for the shear rate to be assumed to be constant, specific analysis methods are nevertheless used to extract variations in viscosity as a function of shear rate (Walters, 1975). Flat-rotor and high-acceleration motors, controlled-torque motors, gas bearings, torque sensors with force rebalancing systems, optical coders and microcomputer control and data acquisition are all recent developments that have been decisive in building the Couette cells now incorporated in modern rheometers.

The aim in building Couette cells is to determine the mechanical or physical properties, in the bulk and at the walls, of a sample under shear (or simply one of these characteristics). Movement can be created either by controlling the rotation speed of the cylinders over time, or by controlling the forces applied (during steady, dynamic or transient regimes). The basic velocity fields obtained are usually interpolations between the boundary velocities. However, there is a wide variety of situations, including local shear rates with a surface of discontinuity⁴), propagation of waves from one wall to another, recirculating flows (instabilities) and turbulent flows.

Mention should be made of the considerable amount of research that has been devoted simply to the study of Couette-Taylor flow instabilities (see for instance Tagg, 1992), in connection with the spin-offs expected in aeronautics and hydrodynamics from an understanding of the mechanisms involved in the transition to turbulence. These studies have been concerned primarily with Newtonian flows so far.

The intentional or accidental application of external forces may considerably modify the organization of a sample of dispersed matter in suspension. In certain cases, thermal effects may play a decisive role.

All kinds of measuring and visualization techniques have been implemented on Couette cells. Non-transparent suspensions have been visualized by nuclear magnetic resonance. Adaptations involving new optical techniques are now being researched, but analysis of birefringence and dichroism in visible or infrared light, neutron diffusion and x-ray diffraction⁵) are all used at present on Couette cells.

The materials used in building Couette cells (or windows in the cells) must of course be carefully adapted to all these techniques. In certain cases, their surface properties (chemical composition, roughness) also have a pronounced influence on the tests performed, by virtue of the type of coupling created at the boundaries of the sample under study.

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⁴) It is worth mentioning a little-known publication by Fernand Charron (1950), a former student of Maurice Couette's, who made microscope observations of the slip of a yield-stress fluid on a smooth glass wall and its adherence to a ground glass wall.

⁵) See, for example, the Hercules program of courses at the European School, Grenoble – Les Editions de Physique.

The largest Couette cells we know are about 1 m across. They were built to study suspensions of particles more than a centimeter in diameter (concrete mixes and mud slides). The smallest gap between Couette cell cylinders is 2 µ. These cells were built to measure the viscosity of lubricants under high shear rates (10^5 to $10^6\,s^{-1}$) such as in internal combustion engine crankshafts, while at the same time controlling the associated heat dissipation effects.

6.2 Couette flows

The idea discussed by Maurice Couette in his thesis, involving the use of boundary conditions to produce simple fields, elementary solutions to the complete conservation equations, has been progressively extended and more precisely stated.

Many didactic works thus present the bases of Newtonian fluid mechanics by starting with a description of Couette's two-dimensional shear. This is the shear that occurs in a thin sheet of fluid placed between two large, parallel flat surfaces, one of which is moved in its plane at a constant velocity while the other remains fixed. The actuating pressure is assumed to be constant throughout the fluid and the fluid is assumed to move in parallel lines to the direction of velocity. The viscosity is thus the ratio of the tangential wall stress to the shear rate. It is also assumed that the Reynolds number remains below a critical value, which is a function of the external disturbances applied.

Couette's shear is also more generally obtained between two curved surfaces moving tangentially to each other and locally parallel, as in the axial slip of cylindrical tubes of any shape, or the rotation of various revolving coaxial surfaces.

Couette flow also occurs in hydrodynamic lubrication. Here, in order to establish the general Reynolds equation, it may be demonstrated that the most general velocity field involves superimposing a Poiseuille-type flow (which is proportional to the pressure gradient and quadratically dependent along the ordinate), and a Couette flow (which is linearly dependent in terms of boundary velocity and ordinate).

Couette flow must now be situated in the general classification of flows adopted by rheologists. It forms part of the class of homogeneous flows, i.e., where the velocity gradient is independent of the space variable. Homogeneous flows are very important in producing stress fields that are themselves independent of space, and consequently fully measurable at the boundaries of the test samples. The objective classification of homogeneous isochoric flows was made by H. Giesekus (1962). In the simple two-dimensional case, if the sample is observed along the strain rate principal axes, it can be shown that it is subjected to a rate of elongation ε and rate of rotation ω and that all homogeneous flows are the result of superimposing this elongation and this rotation. Couette's two-dimensional flow corresponds to the case where the modulus of ε is exactly equal to that of ω.

One may be surprised by the extremely special nature of Couette flow, as it appears in this classification, and we may wonder at its practical consequences and the structural behaviour of the sheared material. However, after demonstrating that any fluid that adheres to the wall is subject to Couette-type shear near the wall, and examining the various results obtained in rheometry and fluid mechanics, it becomes clear that Couette shear is of great relevance.

Incidentally, it is worth noting the genuine importance of elongational flows introduced by Trouton (1906), which are of paramount importance in numerous industrial processes (such as textile spinning).

The fact that the mechanical behaviour laws remain the same, irrespective of observer, shows that Couette-type shear generates clearly defined stresses within a fluid, which must be added to the tangential wall stresses already mentioned. These are normal stresses, and two normal stress coefficients are measured to characterize the material being studied. Like the viscosity coefficient, they depend in general on the shear rate. These three coefficients – the viscosity coefficient and two normal coefficients – define what is referred to as the viscometric properties of a fluid under shear in a steady flow regime.

All these remarks on steady regimes of course apply also to dynamic and transient regimes.

6.3 Couette's corrections and method

When a fluid flows under steady conditions in a very long tube, the velocity (and deviatoric stress) profile in a given cross-section remains independent of the abscissa, provided the section is sufficiently far from the tube entrance and slightly upstream of the exit area. The flow is said to be fully developed.

A long tube of this kind is generally inserted into an installation where there is a change of section at the entrance, enabling the tube to be connected upwards and supplied, and at the exit. Each change of section produces a disturbance in the velocity field, which is different from the fully developed flow both upstream and downstream. Energy losses in the flow, due to dissipation effects, are thus the arithmetic sum of loss in the fully developed zone and losses in the volumes upstream and downstream of the changes in section, both at the entrance and exit.

Maurice Couette was the first to suggest using tubes and installations that were identical at all points operating with the same flow rate, but of different lengths L_1 and L_2. It is thus a quick matter to calculate the loss of energy in a fully developed regime over a distance $L_1 - L_2$ by subtraction. This is the so-called "Couette method", which is now commonly used (see for instance Toms (1958) and Ferguson and Kemblowski (1991)).

Maurice Couette also discussed energy losses in singularities and proposed a method for calculating them. In the case of viscosity measurements in laminar flows, this involves assuming that the energy loss generated by the upstream singularity is equal to that which would have been generated by a length L^* of fully developed flow. In order to deduce the viscosity from an overall energy loss measurement (expressed as the difference in pressure between the upstream and downstream ends of the tube, for example), this measurement is therefore divided by the sum of the real length of the tube L and the correction L^* (which is in a ratio of about 3:1 to the diameter according to Couette; this ratio is predicted in Kestin et al. (1973) as being $0.34 + 0.036\,Re$, in which Re is the Reynolds number). This is known as "Couette's correction", and is now also commonly used (Oka, 1960).

This correction was studied recently in experiments and by numerical computations for viscoelastic fluids and/or yield stress fluids, and it of course depends on the characteristic dimensionless numbers of the flow regime and fluid, as well as on the shape of the singularity upstream.

7. Conclusion

Maurice Couette was, without doubt, an outstanding physicist. His work as lecturer at a Catholic institution, where material resources were limited, did not allow him the facilities and free time he needed to carry out further experiments and explore other theories, and thus win fame in several areas of physics. However, his repute in fluid mechanics is fully justified by his pioneering work.

Beyond this, and more generally speaking, Maurice Couette is unquestionably one of the founders of rheology, the science of flowing matter. His contribution to the study of liquid viscosity, the interest and spin-off from which have been discussed briefly in this article, are the fruit of a very modern approach, which can best be expressed by quoting the first two sentences from the introduction to his thesis:

"The extensive research carried out up to the present time to establish the relationships between the internal friction coefficient and the other physical properties or chemical structure of liquids has not yet led to the formulation of any of these laws, which deserve a place in science by virtue of their experimental certainty or by their precise adaptation to theory. Before undertaking new investigations in the same field, therefore, I felt it wise to subject the following two fundamental questions to careful examination:

1) Is the internal friction coefficient a well defined physical quantity?

2) What rules must be followed to determine its value?"

This contains, in embryonic form, the characteristic aspects of modern rheology, with macroscopic laws and physical chemistry, rheophysics and micro-macro transitions, rheometry and even interface problems. Maurice Couette's concern for interdisciplinarity, which is one of the keys to success in rheology, is clear in these few lines written in 1890, and shows how much his approach is of relevance today.

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Appendix

This appendix gives a comprehensive list of Maurice Couette's publications. Boldfaced titles are for references that are most easily available.

(1887) **Oscillations tournantes d'un solide de révolution en contact avec un fluide visqueux.** (Abstract by the author) CR Acad Sci 105 (2nd semestre):1064–1067 Research report presented by Mr. Poincaré (Hydrodynamics), withdrawn from the secretariat at the author's request in 1888 (CR Acad Sci 107:412)

(1888) **Sur un nouvel appareil pour l'étude du frottement des fluides.** CR Acad Sci 107 (August 6):388–390 Note presented by M. Lippmann (Molecular physics)

(1888) **La viscosité des liquides.** Bulletin des Sciences Physiques 4:40–62, 123–133, 262–278

(1888) **La viscosité des liquides.** Report taken from the Bulletin des Sciences Physiques (text with sections 13 to 16 added). Georges Carré, Paris, 48 p.

1889 – Oral presentation given at the sessions of the French Physics Society with a summary in the Society's Bulletin.
- March 1 (Bulletin SFP:60–61): presentation of two experiments (cylinders and tubes) with a view to verifying the Navier equations, and of results using water.
- June 7 (Bulletin SFP:108–109): new laws for fluid movements deduced from Navier in agreement with observations.

(1890) **Etudes sur le frottement des liquides.** Doctorat ès-sciences Physiques (May 30) Faculté des Sciences de Paris – 1st thesis, Gauthier-Villars et fils, Paris, In-4°, 119 p

(1890) **Distinction de deux régimes dans le mouvement des fluides.** Journal de Physique série 2, IX (Sept.):414–424

(1890) **Corrections relatives aux extrémités des tubes dans la méthode de Poiseuille.** Journal de Physique série 2, IX (Dec.):560–562

(1890) **Etudes sur le frottement des liquides.** Annales de Chimie et de Physique serie VI, 21:433–510

(1891) Applications de la théorie des pressions de Cauchy aux phénomènes capillaires. Compte-Rendu du Congrès Scientifique International des Catholiques, Paris (Avril 1891). Alphonse Picard, Paris, 7:103–113

(1891) Définitions et lois fondamentales de la chimie – Causerie pédagogique. Revue des Facultés Catholiques d'Angers, 1ère année no. 2:164–180

(1892) **Sur la constance de l'équivalent électrochimique.** Journal de Physique serie 3, I:350–352

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(1894) La Science Catholique, 9th year – Bulletin de Physique, 1:80–96

(1895) La Science Catholique, 9th year – Bulletin de Physique, 4:358–372, 6:571–580, 9:854–868, 11:1049–1056

(1895) Réflexion et réfraction du son. In-8°, 24 p and Congrès Scientifique d'Angers: 266–287

(1895) Analyse du livre de l'abbé Cottereau: Notions de Chimie. Revue des Facultés Catholiques de l'Ouest, 5th year, 2 (Dec 1895):318–321

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(1899) La Science Catholique, 13th year, 11-Bulletin des Sciences Physiques:1039 – 1054

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(1900) **Sur la théorie osmotique des piles – I et II.** Journal de Physique serie 3, IX 200 – 208, 269 – 279

(1900) **Sur la théorie osmotique des piles.** Reprinted from Journal de Physique, In-8°, 19 p

(1900) **Expériences favorables à la théorie de M.W. Nernst.** Journal de Physique serie 3, IX:652 – 654

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Complementary information

The examiners' reports on Maurice Couette's doctoral thesis and the records stating that his doctorate was awarded may be consulted at the National Archives in Paris (Series AJ16, from the Paris Education Authority, nos. 5535 and 5267), together with Couette's private school headmaster's file (AJ16 no. 6189), where details of his career in Paris are provided either by himself or by authorized sources.

Certain biographical details provided in the article are based on authentic documents made available to the authors by Maurice Couette's family.

The text of the speech made at Maurice Couette's golden wedding ceremony may be obtained on request from the family, represented by J.M. Couette[3]. This was published in the Bulletin des Facultés Catholiques de l'Ouest, 43rd year, nos. 3 – 4 (July – October 1936), pp. 21 – 26.

Eugène Ducretet's career was described by his grandson Bernard in the journal Ondes Courtes-Informations, no. 18 (January – February 1971). Various items may also be consulted at the Bibliothèque d'Histoire des Sciences et des Techniques at the Conservatoire National des Arts et Métiers, 2 rue Conté, Paris, where technical documents from the Ducretet bequest are deposited.

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Correspondence to:

Prof. J.M. Piau
Laboratoire de Rhéologie
BP 53 – Domaine Universitaire
38041 Grenoble Cedex 9
France