The Mechanics of Fluid - Particle Systems

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ABSTRACT

The study of the interaction of particles moving relative to fluids has had a long history and has led to many useful operations particularly in modern agriculture. Of special interest is the trajectory of particles and crop components but, until recently, it has not been possible to easily determine these. However with the recent publication of a trajectory plotting system and an associated monograph giving examples of its application, this need has now been met. Both should find ready application in education, research and design in the agricultural engineering industries. Copies of the trajectory plotting program and the associated monograph can be obtained at the addresses given in Section 4 below.

Keywords: Fluid, particle, mechanics, trajectory, drag, computer program, Australia

1. INTRODUCTION

The movement of particles in a fluid is a common occurrence. Many natural processes such as seeds blowing in the wind, raindrops falling to the earth and sand grains carried in a stream involve such interactions. The informal observation of these over the centuries has, no doubt, informed the observer and guided the practical evolution of many useful developments. However any formal conclusions, if drawn, are lost to us in the mists of history.

Further observation of these phenomena probably raised the question of why some particles were transported further than others and this ultimately led to the use of these processes being exploited to achieve desirable goals such as the separation of chaff from grain in the wind or of gold from gravel in a natural or constructed water stream.

Like the traditional agricultural processes such as winnowing of grain in the wind and spreading of seed by hand, many modern machine operations in agriculture also involve the relative movement of particles in a fluid and require a detailed understanding if the machines are to be designed on a more analytical basis.

However it is only in relatively recent times that it has been possible to easily undertake this analysis with the use of the digital computer. Hence it is now possible for students and engineers to solve a range of typical problems that hitherto have been impossible or at least to gain insight into the processes and hence into operation of the machine and environmental elements that involve them.

2. EARLY APPLICATIONS IN AGRICULTURE

Like many developments where natural phenomena have been adapted to useful purposes, fluids have been used from earliest times to separate and convey particles. Perhaps the earliest reference to such use in agriculture is the biblical reference to winnowing in the book Ruth (3:2) dated some 10 to 12 centuries BC. Similarly the earliest reference to a winnowing machine is of a hand cranked rotary winnowing fan shown in a pottery diorama from the Han Dynasty in China ((206 BC – 221 AD) (Needham, J. (1984)).

The hand and later machine harvesting of seeds initially involved the cutting, plucking or stripping of heads and their later threshing to detach the chaff from the grain. The grain and chaff were then separated in an air-stream (usually combined with a sieving or riddling process on a perforated sheet) in a separate winnowing process by hand or machine. With the further development of the harvesting processes it was logical to include this winnowing or similar cleaning process in a single mobile harvesting machine. Hence the working principle and the elements of many modern mobile machines, for harvesting a wide range of crops, were settled.

One of the simplest concepts in fluid – particle mechanics is that of the terminal (or settling) velocity of a falling particle. This parameter has been identified because it is recognised as a naturally occurring value and a characteristic of any fluid – particle combination. It is of special interest because it is the only condition for which we accurately know the fluid drag force (equal to the net gravity force) and for which we can easily calculate the drag coefficient.

The terminal velocity (or the related floating velocity) has been used as a basis for specifying the characteristics of particles in fluids and for designing one dimensional (vertical) separation systems. However it does not provide an adequate basis for predicting the trajectory in common, more important and much more interesting two dimensional problems.

3. THEORETICAL STUDIES

3.1 Particle Characteristics

The theoretical study of the interaction of solids with fluids had its origins in the analysis of forces on plane and curved surfaces. This was then applied to the interaction of fluids with solid objects such as fixed cylinders and buildings and with other objects such as sails and aeroplane wings which have a variable, but controlled attitude to the relative motion. (Prandtl and Tietjens, 1957).

When small, solid particles are involved the interest is usually in predicting their trajectory. Here particles are totally 'free' to move (translate) and rotate as a result of the gravity and the fluid drag forces and generally do so with a complex motion. The common practical application in agriculture usually only requires the prediction of particle motion and the trajectory at the macro-level.

Early experimental research on geometric shapes focused on the properties (often measured in the context of terminal velocity) that were relevant to the theoretical analysis (Schiller, 1932; Pettyjohn and Christianson, 1948). These concepts were later applied to mineral and other particles in the chemical and mining industries (Wadell, 1934). Much of this work was quite general in nature and therefore could be applied in other industries such as agriculture where the particles could also be specified in similar terms.

3.2 Trajectory Prediction

Publications concerned with the prediction of particle trajectories in agriculture may be divided into two main sub groups.

3.2.1 Distribution Processes

These consider the spreading of dry particulate material from ground or aerial based machines; the interest is in the final distribution of the materials on the target, usually the soil. Published work shows the influence of the size, mass and shape of the particles as well as the magnitude and in some cases the direction of the projection velocity.

Mennel and Reece (1963) developed a numerical solution to the equations of motion of fertilizer particles on an early digital computer while Reints and Yoerger (1967) and Dobler and Flatow (1969) used an analogue computer for this purpose. Yates et al., (1973) based their calculation using a digital computer on a relationship between actual and terminal velocity conditions. All use approximations to the drag coefficient relationship and were limited to a particular set of conditions including still air.

3.2.2 Separation Processes

Here the interest is in illustrating how the physical arrangement affects the extent to which the various fractions are separated, usually with either a horizontal or vertical air stream. The process is interpreted and optimised in terms of the respective trajectories using variables such as the magnitude of the air stream velocity and the magnitude and direction of the injection velocity.

Using a digital computer Kashayap and Pandya. (1965), Gorial and O'Callaghan. (1991b) and Adewumi et al., (2006) investigated trajectories and hence conditions to promote separation of two fractions in a confined, horizontal air stream. Farran and Macmillan, (1979) and Gorial and O'Callaghan. (1991a) used a prediction of trajectories to investigate conditions for optimum separation of two fractions in a vertical air stream.

In summary all of the above are limited to a particular physical situation and rely on an approximate form for the drag coefficient - Reynolds number relationship. Hence while they may be satisfactory for the specific research objectives chosen they have limited didactic value and are not available for general use in the profession and educational communities.

Perhaps the most powerful and immediately useful theoretical work in the prediction of particle trajectories was that by Lapple and Shepherd (1940). They used the traditional analysis of fluid forces on solid particles to develop the equations of motion of particles in a range of configurations. These were applied to the manual calculation of the trajectories of very small droplets which effectively behave as solids.

Because the calculation involved in using this work was so tedious it was not widely applied until digital computers became available and it was applied by the author in the present work. Its value and its application to a range of problems of interest in agricultural engineering education and research has now become apparent.

4. PRESENT WORK

4.1 Introduction

The author's interest in fluid particle mechanics and in particular the prediction of particle trajectories arose out of the need to develop suitable course materials for training of professional agricultural engineering students. It was also driven by a certain frustration with the fact that existing methods were largely limited to the use of terminal velocity as a basis for separation processes. This occurs in the context of a range of separation, distribution and other problems that require an analysis in two dimensions.

The help of Winters, G. (Personal communication, 1970) with an early version of the algorithms and the work of Computer Science students at the University of Melbourne in developing a version of the program for the Macintosh computer is acknowledged. The use of the latter is illustrated in Macmillan (1999).

A more general solution to this problem has not been available until the recent publication of the present work. This is published in two parts:

i. A trajectory plotting system: http://eprints.unimelb.edu.au/archive/00001513/
ii. An associated monograph: http://eprints.unimelb.edu.au/archive/00001514/

Both can be downloaded free of charge from the University of Melbourne website at the addresses given. No hard copies are available.

4.2 Trajectory Plotting System (TPS)

This is in the form of a computer program which calculates and plots the trajectories for up to 10 particles projected at any angle (or dropped) in any fluid with a velocity at any angle. The particle is specified by its equivalent diameter and mass and the fluid by its density and viscosity. The drag force is calculated on the basis of a user chosen drag coefficient – Reynolds number relationship and the velocity of the particle relative to the fluid which is calculated for each time step. Further details on the use of the program are available from the User Manual and the associated monograph (see on).

It is important to emphasise that the program is quite a general one and can be used for any particles in any fluid for which the standard drag force equation applies and for which the relevant data are available. However it cannot be used to calculate the effect of particle spin nor for the prediction of trajectories in three dimensions, ie, where the vector representing the velocity of the fluid does not lie in the vertical plane through the vector representing the velocity of the particle.

In terms of research, while this program will not totally eliminate the need for experimental work, it will provide guidance about the relative effects of the different variables and so guide the research along the most efficient lines.

If it is argued that we do not have sufficiently good data on particle properties to justify the use of such a program, the author would respond that perhaps this is because, up till recently, our computational capacity did not justify their measurement. This program will provide a readily available but powerful tool to aid in the design of new machines and insights into their operation that would justify a new round of data collection to improve its accuracy.

4.3 The Mechanics of Fluid - Particle Systems

This monograph provides the background to the program and the associated theory. Following the introductory review in Chapter 1, the interaction of bodies and fluids moving with a relative velocity is considered in Chapter 2. This is illustrated by the drag coefficient - Reynolds number relationship for bodies of various shapes and for some agricultural materials. In Chapter 3 the concepts of terminal and floating velocity are introduced and their application as a basis for the separation of two fractions in a mixture is discussed. Chapter 4 introduces the two - dimensional, general solution to the fluid - particle trajectory problem and explains the basis of the algorithm on which it is based. Chapters 5 to 16 detail a number of applications of the program, mainly in agricultural engineering.

4.4 Validation of Computer Program

Before publishing the TPS program it was thought desirable to validate the program against already reported results and thereby increase the confidence in using it in new situations. This was done by plotting the range (maximum distance) taken from reported results against those obtained by the TPS using the same particle and fluid properties. Figures 1 and 2 show that the values predicted by the TPS were within 5% of the reported results for ranges varying from less than 0.1 m to more than 20 m. This suggests that there is an excellent correlation between the two sets of values.

It should be noted that this validation is not wholly conclusive since the reported values and those from TPS are essentially based on the same theory - they may of course both be in error by similar amounts and still be well correlated. Nor does this result imply anything about the validation of either set of results against what might be obtained in a practical situation. Readers are referred to the papers cited.

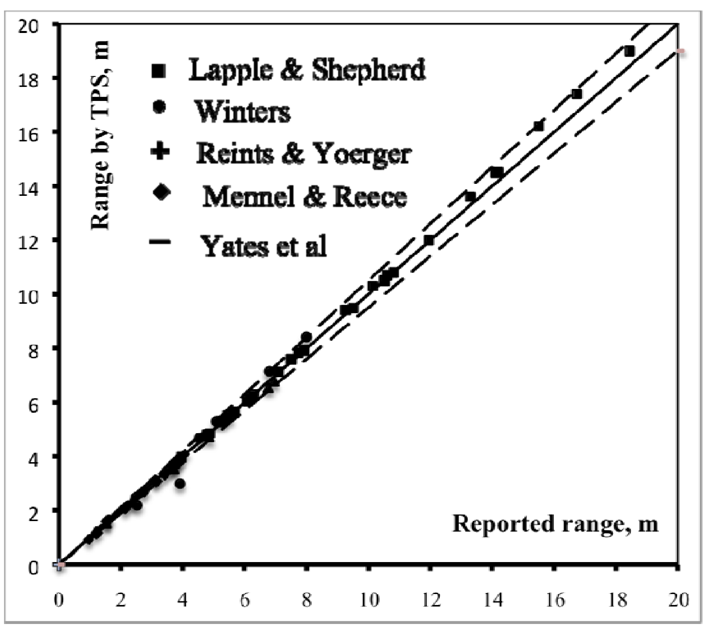

Figure 1: Correlation of values of range from reported work compared with data from trajectory plotting system; values from 1 to 20 metre. Dashed lines shows ± 5%.

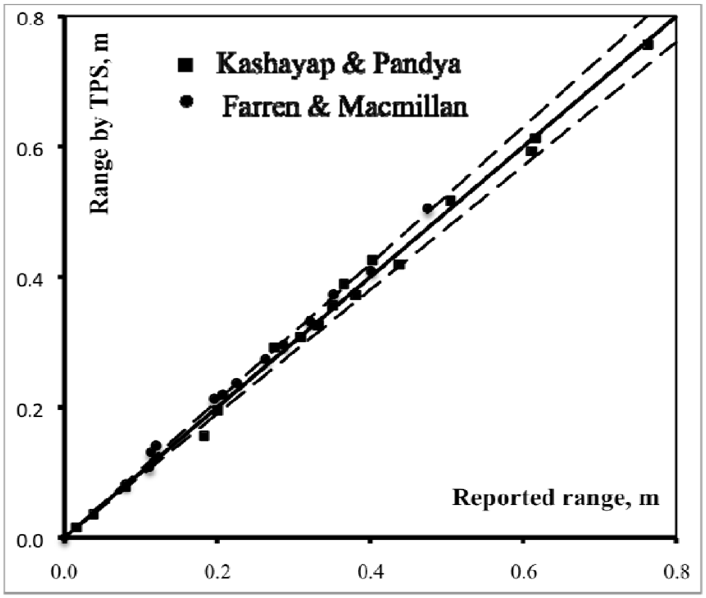

Figure 2: Correlation of values of range from reported work compared with data from trajectory plotting system; values from 0.01 to 0.8 metre. Dashed lines show ± 5%.

5. CONCLUSION

The trajectory of particles moving relative to fluids is an important aspect of fluid – particle mechanics. The trajectory plotting system discussed above provides an important tool for education, design and research while the associated monograph illustrates its use in a number of applications in agriculture. The author believes that it is by developing and making such material freely available that the agricultural engineering profession can best promote itself and the industries which it seeks to serve.

6. ACKNOWLEDGEMENT

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