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ABSTRACT

The present work reports a very important experimental data for heat transfer calculations in multi phase gas-solid flow systems. The experimental setup is designed in the present work to facilitate the variation of many parameters over a wide operating range. To obtain symmetrical distribution for solids, the test section pipe is installed vertically and to minimize radiation effects, the considered temperature ranges were moderately low. This made the experimental data also helpful for the development of theoretical two dimensional heat transfer models for turbulent gas-solid pipe flows.

All experimental work were done at a constant heat flux condition. The properties were calculated based on the logarithmic mean temperature difference. To the author's knowledge, the present data despite their importance and need in many engineering applications are not available in the literature, especially in the present considered ranges of *Reynolds* number, loading ratio, particle size and material densities.

The study covers the heat transfer measurement in gas-solid flows in which the solids are: raw phosphate from RuseifaJordan, soil from Irbid, sand from Swaileh, and copper particles. Addition of Ruseifa phosphate showed the maximum augmentation of *Nusselt* number of gas-solid flow while the effect of particle size on the value of *Nusselt* number was found to be negligible over a range of average particle size of 75 μm to 600 μm. The effect of *Reynolds* number on the value of *Nusselt* number for these gas-solid flows, over a range of *Reynolds* number of 10000 to 34000, was the dominant effect as supported the present results. The effect of loading ratio of solids was studied in a range of 0.0 to 0.34 where it was concluded that the increase in loading ratio enhances the value of the *Nusselt* number of the gas-solid flow.

بسم الله الرحمن الرحيم

ملخص الرسالة

يقدم هذا العمل معطيات هامة لحسابات انتقال الحرارة في انظمة جريان غاز - صلب معلق. الجهاز التجريبي الذي استخدم في التجارب صمم ونفذ ليسهل استخدام وتجريب متغيرات للجريان على مدى واسع. وللحصول على توزيع متماثل للصلب في الأنبوب المسخن لجا الباحث لجعل الأنبوب المسخن عمودياً. ولتقليل التاثير الاشعاعي للحرارة استخدمت درجات حرارة معتدلة نسبياً. وهذا بدوره يجعل المعطيات والقراءات التجريبية اكثر مساعدة لتطوير نماذج نظرية ثنائية الأبعاد للجريان المضطرب لغاز - صلب معلق في الأنابيب.

جميع التجارب أجريت تحت ظرف تدفق حرارة ثابت على الجدار. الخواص حسبت بناءً على درجة الحرارة المتوسطة اللوغارتيمية. وفي حدود معرفة المؤلف فإن النتائج والقراءات الحالية بالرغم من اهميتها والحاجة إليها في كثير من التطبيقات الهندسية إلا انها غير متوفرة في متناول الباحثين والمهندسين. وخاصة في المدى الحالي لكل من (رقم رينولد) ونسبة التحميل للصلب وحجم حبيبات الصلب وكثافة الصلب المستخدمة.

الصلب الذي استخدم كان فوسفات من الرصيفة ورمل من صويلح وتربة من اربد وحبيبات نحاس. اقطار الحبيبات تراوحت ما بين ٧٥ إلى ٦٠٠ ميكرون (ورقم رينولد) كان ما بين ١٠ر٠٠٠ و ٣٤ر٠٠٠ بينما نسبة التحميل تراوحت ما بين صفر و ٠ر٣٤ كغم صلب/ كغم هواء. فوسفات الرصيفة اظهر اكثر كفاءة في تحسين (رقم نسلت) بينما بشكل عام اثبت الدراسة ان إضافة الصلب إلى الهواء يحسن من كفاءة إنتقال الحرارة.

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BY

Emadeddin Yousef Hasan Tanbour

B.Sc. Mech. Eng. 1987

April 1990

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Dr. Taha K. Al-Doss	(Supervisor)		8/7/90
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Dr. M. A. Kolb	(Committee member)		July 18, 90

TO MY MOTHER

AND DEPARTED FATHER

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After raising my prayers to Allah, the author wishes to convey his thanks and acknowledgements to *Dr. Taha Al-Doss* and *Dr. Tharwat W. Abou-Arab* for their invaluable time and effort without which this piece of work could not have been accomplished.

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Emadeddin Y. Tanbour
May, 1990

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CHAPTER 1

HEAT TRANSFER IN GAS-SOLID SUSPENSION FLOWS

(INTRODUCTION AND LITERATURE REVIEW)

Chapter 1

HEAT TRANSFER IN GAS-SOLID SUSPENSION FLOWS

The subject of two phase flow, particularly the gas-solid suspension flow has been studied for many years. Most of these studies were concerned about the momentum transport of the solid-fluid systems, because the original application of these studies was mainly the pneumatic transportation.

Currently, the study of heat transfer phenomenon has been encouraged so as to meet the recent technological applications of high heat transfer rates in a minimum heat transfer area, i.e, maximum compactness and minimum cost of heat transfer equipment.

As reported by *S.L.Soo* [24], there are many multiphase systems among engineering equipment and processes. For the problem of this study, gas-solid flows can be faced in pneumatic conveyors, dust collectors, fluidized beds, heterogeneous reactors, metallized propellant rockets, aerodynamic ablation, xerography, cosmic dusts and nuclear fallout problems and cooling.

As heat transfer media, gases and liquids have some limitations and considerations which need to be overcome when high levels of heat flux are required. Liquids have more efficient heat transfer characteristics than gases because of their higher density and thermal conductivity. Inspite of these previous merits,liquids have some restrictions when they are used in high temperature applications. For example, high pressure is needed to prevent change of phase, which causes instabilities and boiling problems.

Gases can be used for high temperature applications but they have lower thermal conductivities and lower density-specific heat (ρCp) product values, which lead to smaller heat transfer coefficients and hence, larger heat transfer area.

The above mentioned deficiencies can be overcome by the addition of solid particles to the gas stream. In 1957 it was the first time that the pioneering engineers *Farbar* and *Morley* [13] made their laboratory experiments by the addition of alumina silica catalyst to flue gases in order to recover waste heat and generate steam. Since that time, interest in gas-solid suspensions as a heat transfer medium was renewed. However, this interest, until the end of 1970's [13],had received relatively little attention from the scientists.

Augmentation of heat transfer rate by the addition of solids played a major role in the field of nuclear reactor cooling. The same heat transfer rates can be obtained at a lower system pressure and smaller system size. The influence of suspended particles on the process of heat transport was studied and discussed by numerous researchers. An obvious point of agreement is that solid particles enlarge the volumetric thermal capacity of the flow, which in turn decreases the heat transfer area for the same heat

E.E. Michaelides [21] tried an analytical solution for the governing equations of gas-solid flow. He assumed that the fluctuating product term $\overline{v'\phi'}$ is equal to $-\varepsilon_\phi \frac{d\overline{\phi}}{dy}$ where ε_ϕ is the diffusivity of the transported quantity ϕ and y is the radial axis. He compared the analytical *Nusselt* number versus loading ratio with experimental results reported by *Farbar* and *Depew*[16] for *Reynolds* numbers of 15300 and 26500.

Abou-Arab and *Abou-Ellail* [4] presented a computation model for the momentum and heat transfer in turbulent gas-solid flows. Their predictions were compared with experimental results reported by *Tien* and *Quan* [27] for glass and lead particles for 30 μm diameter, and a good agreement was obtained.

Analytical solutions for heat transfer in gas-solid flows were considered by *Tien* [27] in 1961 and *Elgebeily* and *Abou-Arab*[15]. These solutions were subjected to many simplifying assumptions, which limited their use in many practical applications. To my knowledge the work reported recently in 1989 [4] is the most comprehensive one with minimum assumptions, but it still needs some elaboration concerning the determination of eigenvalues and eigenfunctions of the governing differential equations.

Zeatoun et al. [30] extended the model of *Abou-Arab* and *Abou-Ellail* [4] for different two phase gas-solid developing and fully developed turbulent flows.

Concerning the previous theoretical work, few investigations of the behavior of gas-solid suspension flows for a wide range of operating conditions had been conducted since the middle of this century, to the author's knowledge, the following is a quick revision of the most important and available experimental work.

Tien and *Quan* [27] studied the heat transfer to gas-solid flow in a uniformly heated vertical tube. *Reynolds* number used were 15000 and 30000 only. Solids used were 30 μm glass particles. Suspending gas was atmospheric air, with a range of loading ratio of 0.0 to 3.0 on mass bases. Heat was added via a thin shell tube that

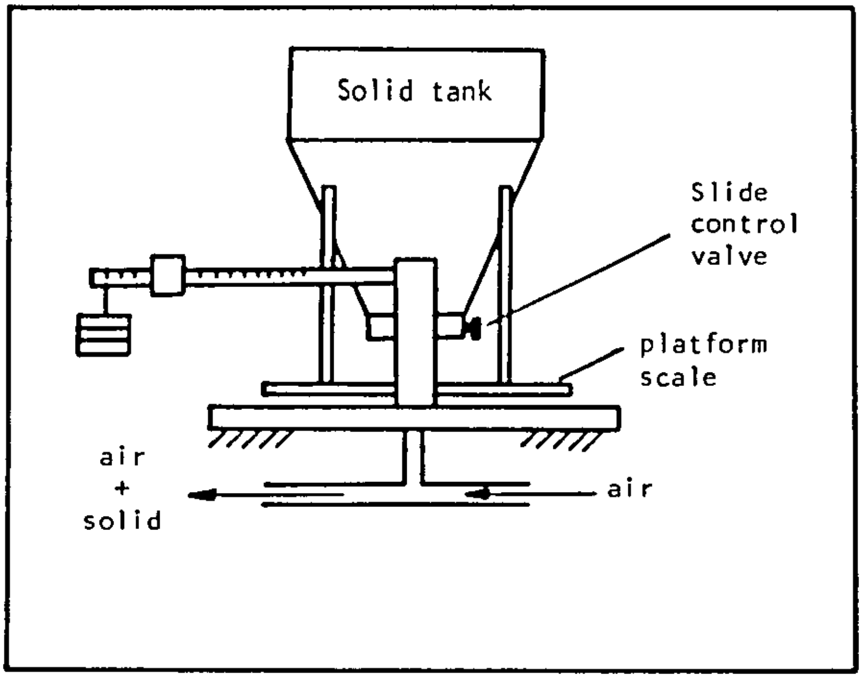

Figure (1.1): Platform scale used in ref. [9].

Tien and *Quan* [27] reported that the addition of solids to the gas has two main effects on heat transfer; first, the solids increase the volumetric heat capacity of the flowing medium and therefore increase the heat transfer rate; second, as the loading ratio increases entrance length increases.

Chu and *Depew* [9] used a uniformly heated circular pipe. *Reynolds* number was ranged from 12000 to 30000. Solids used were glass particles of 30 μm, 62 μm and 200 μm diameter. Suspending gas was air with a loading ratio range of 0.0 to 8.0 kg solid per kg air.

Wall temperature of the test section tube at outlet was $193°C$ as a maximum. Test section specifications were 1" and 2" vertical circular pipes of 7.5 m long; 3.3 m as a developing section, and 4.2 m as a heated section. Solids were fed to the system through the throat of a converging-diverging nozzle. They reported that as the size of the solid particles is reduced the effect of solid addition is increased towards the increase in heat transfer coefficient.

The experimental work of *Peskin* and *Briller* [7] was carried out on a uniformly heated horizontal tube, *Reynolds* number 130000 only. The solids used were glass particles of 170 μm, 511 μm and 896 μm in diameter and the suspending gas was atmospheric air with a fixed loading ratio of 2.0. The maximum wall temperature was 260 C. The test section was 3 " diameter tube of 6.0 m long divided into 3.0 m preheated section and 3.0 m heated test section.

Their results showed that for considered high *Reynolds* number flow 130000, the heat transfer coefficient was equal to that of the pure gas at the same *Reynolds* number, and independent of solid loading ratio, heating or cooling and particle size.

Depew and Cramer [12] used a horizontal uniformly heated tube, flows of Reynolds numbers of 10000, 15000 and 30000 were considered. The solid phase was glass particles of 30 μm and 200 μm diameter, while the carrier was air up to 7 kg solid per kg gas. Temperature level as140° C. Test section of 3/4" diameter with about 4.0 m (2 m as a developing part and 2 m as a heated section).

The purpose of their work was to investigate the effect of stratification on the heat transfer characteristics of system. Their obtained results showed that *Nusselt* number on the bottom side of the tube was about 2.5 times of that on the top side.

Maeda and *Saigusa* [20] used a vertical rectangular test section. One side of it is kept at 70° C using electrical heating leaving other sides unheated. *Reynolds* numbers were varied up to 35000. Glass particles of 55 μm with air as suspending medium were used. The solid loading ratios were relatively high up to 10 kg solid per kg air. Dimensions of the test section were 20 x 15 cm^2 crosssection with 40 cm length.

Their conclusions can be summarized in the following two comments: (1) The addition of solid to a low turbulent flow causes a large increase in heat transfer coefficient in the region of loading ratio of 0.0 to 0.8 and the rate of increase becomes smaller and linear in the region of loading ratio above 0.8, and (2) Addition of particles to a high turbulent flow causes a smaller increase in the heat transfer coefficient than in the case of low turbulent flow.

The reason was, as they found, that the addition of particles to highly turbulent flow reduces the turbulent intensity, hence, the increase in heat transfer coefficient is mainly performed by superficial heat capacity of working fluid-solid suspension.

Hasegawa et al [18] used a closed loop system containing a vertical circular test pipe. The test sections was uniformly heated. *Reynolds* number was up to 20000. Graphite powder of 4.0 to 44.0 μm size was used as a solid phase. Suspending gas was helium carrying solid particles at loading ratios up to 4.0 and the temperature level was up to 1173 K. Test section was 18 mm diameter and 1000 mm long. Results tial conditions), e.g: whether constant heat flux or constant wall temperature was considered.

The previously mentioned shortcomings motivated current experimental work. As will be explained next, the present work covered a range of *Reynolds* number,loading ratio,material density and particle size which corresponds to the flow in many practical applications and blocks some gaps between the previous data.

CHAPTER 2

EXPERIMENTAL SET-UP

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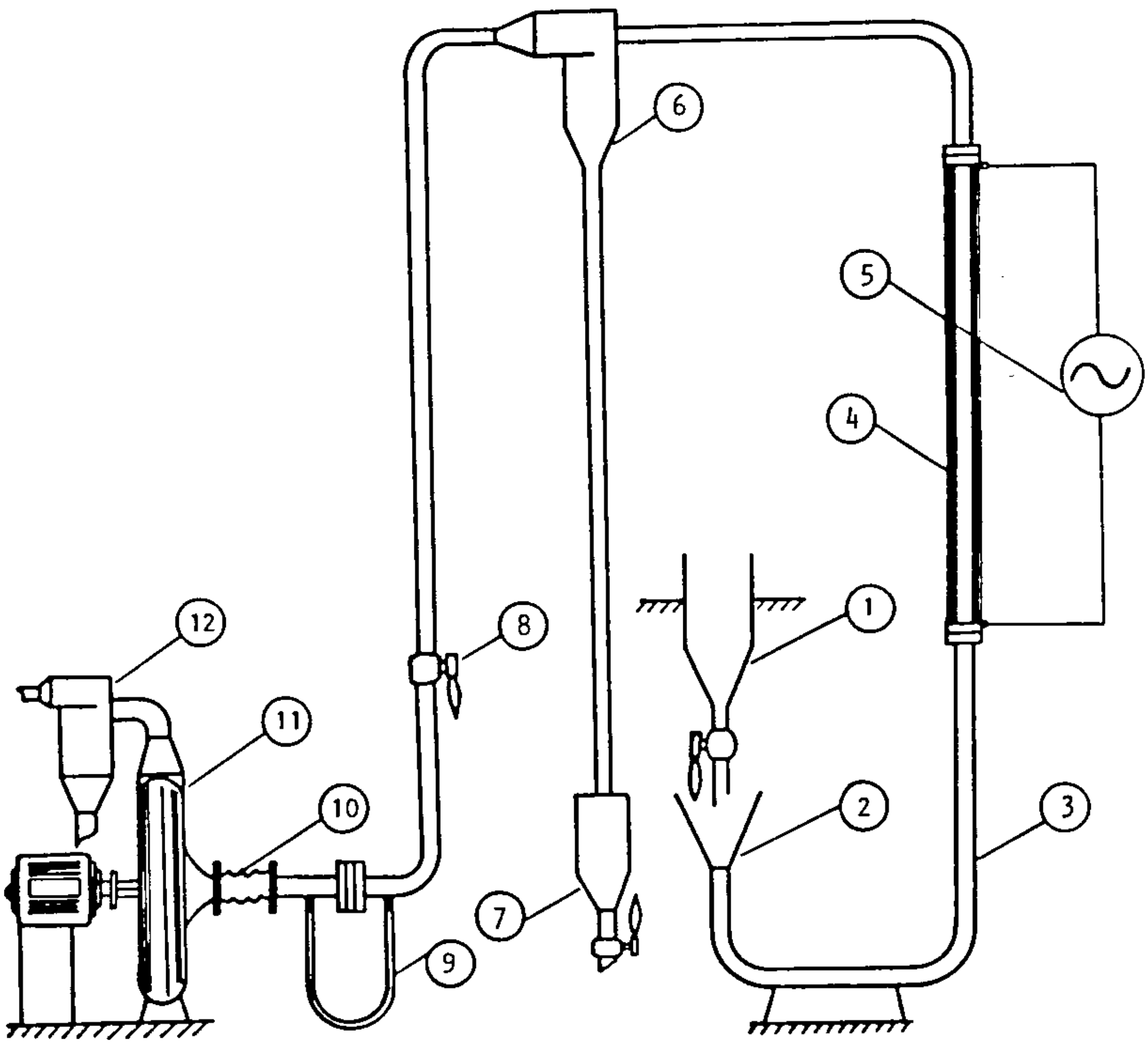
EXPERIMENTAL SETUP

2.1 Introduction

The experimental test rig that was used in the present work, was completely manufactured at the workshop of *Jordan University of Science and Technology* [5] , as shown in Figure (2.1). Details of this section is as follows.

2.1.1 Air Blower

In the present test rig, the air blower used was designed and manufactured at the university workshop. According to [5], the following specifications of the air blower prevail:, Driving motor power = 7.5 kW. Maximum air flow rate = 106 m /hr. RPM = 1000, The blower is of a centrifugal type, it produces the source of air that is induced in the loop to carry the solids. The blower intakes air from the loop and discharges it into the atmosphere. The air flow rate is controlled by a ball valve fitted at the inlet of the blower prior to the air flow meter as shown in Figure (2.1).



1. Solid feeding tank.
3. Approach section.
5. Electric power supply.
7. Storage tank.
9. Orifice flow meter.
11. Air blower and motor.

2. Bell mouth
4. Heated test section.
6. First cyclone separator.
8. Ball valve.
10. Flexible coupling.
12. Second cyclone separator.

Figure (2.1): Experimental set-up and main components.

2.1.2 Solid Phase Feeding System

As shown in Figure (2.2), the solids are fed into the feeding tank at a rate which is controlled using a ball valve fitted at the lower part of the feeding tank, the solids then leave to the bell mouth and are consequently induced inside the loop.

2.1.3 Approach Section

This section is a straight pipe of two inches nominal diameter, the purpose of this section is to carry the gas-solid suspension flow to the condition of hydrodynamical full development. In this manner, the study of the heat transfer to the gas-solid suspension flow, in the heated section, will ensure a hydrodynamical fully developed flow.

2.1.4 Heated Section (Test Section)

This section is a threemeter long pipe with an inner diameter of 5 cm, and wall thickness of 2.5 mm. The pipe is a galvanized commercial steel one. Heat is supplied to the test section using an electrical resistant heating system which consists of the main heater and the guard heater.

Thermocouples are fixed along the pipe at 18-stations. As shown in Figure (2.3 a), the first eleven thermocouples are fitted ten centimeters apart, and then four thermocouples are fitted twenty five centimeters apart, the last one hundred centimeters of the pipe are supplied by three equidistant thermocouples, thus covering the whole length of the heated pipe. Moreover, three nipples are welded at three stations on the

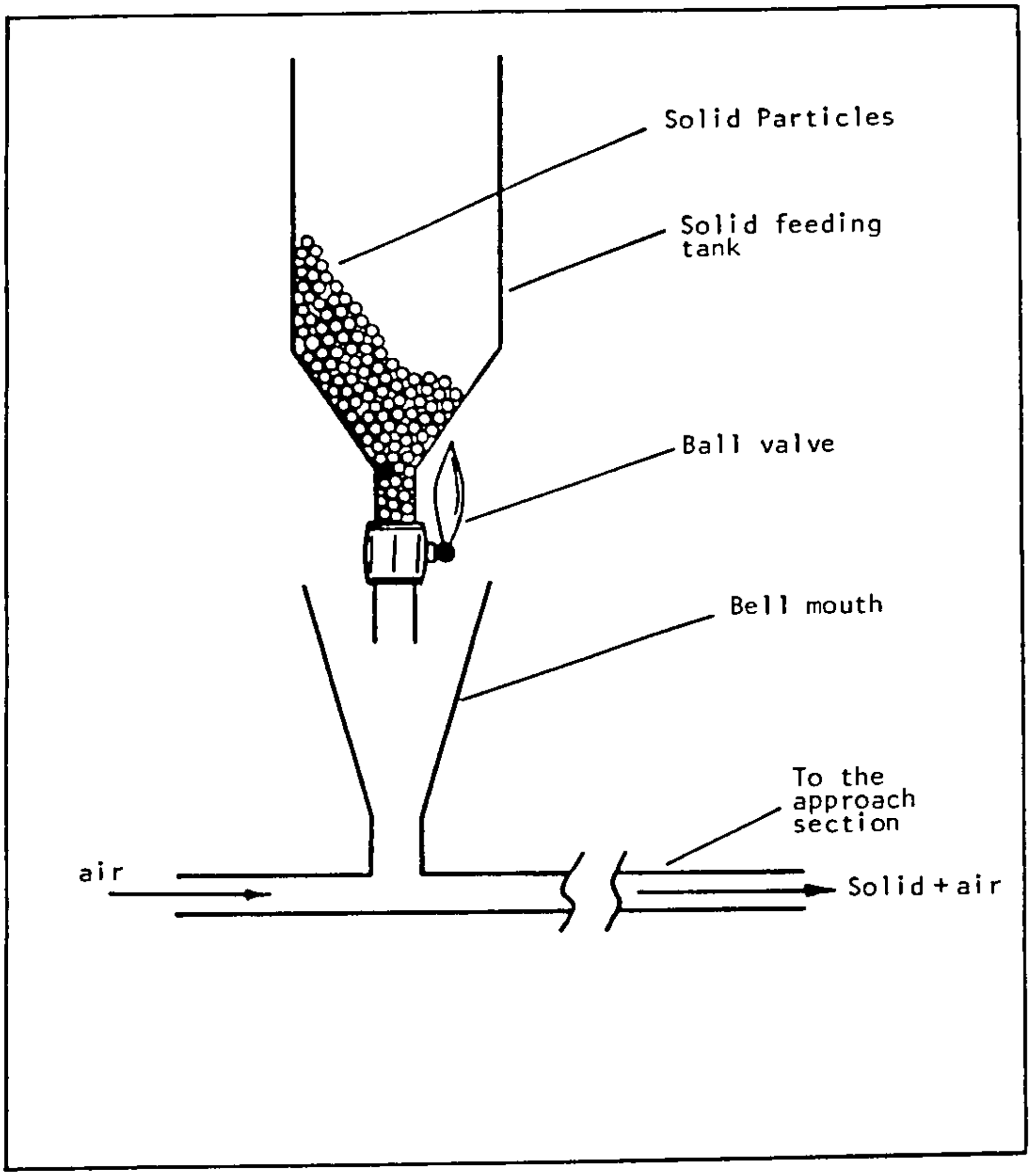


Figure (2.2): Details of solid feeding system.

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