Experimental Investigation of Load Exerted on a Double-Cone Insert and Effect of the Insert on Pressure along Walls of a Large-Scale Axi-Symmetrical Silo

S. Ding[1], A. Dyrøy[2], M Karlsen[2] , G. G. Enstad [1, 3] and M. Jecmenica[3]

1. Department of POSTEC, Telemark Technological R&D Institute, Kjønes ring, 3918, Porsgrunn, Norway

2. Technology of Materials & Processes, Hydro Aluminium Metal, Norway

3. Department of Process Technology, Telemark University College, Kjønes ring, 3914, Porsgrunn, Norway

Abstract

Applications of flow aid devices (commonly referred as inserts) improve the silo discharging mode. Considerable efforts have been made in finding best configurations between the inserts and silos to achieve the optimal functional results. In the present investigation, experiments were carried out to measure the loads imposed on a double cone insert by the particulate solids (free flow sand) when it was fitted within an axi-symmetrical large scale silo. A concentric filling / discharging was implemented to fulfil such measurements. Pressures developed along the walls of the silo were also measured. Analyses of the measurement results showed that: 1.) the loads on insert were rather stable in total, but appeared to be asymmetrical at the end filling; 2.) a sudden increase was observed of the loads on the insert at the transition from filling to discharging, this increase did not last soon afterward; 3.) such loads decreased slowly but remained rather high for large part of discharge. Effects of the double cone insert on the pressures along the silo walls were discussed.

Keyword: Experimental investigation, a double cone insert, shallow hopper, loads and pressure, wall stress, a large scale silo, concentric filling, load measurement

Introduction

A prerequisite to ensure the structural integrity in silo design would be a close estimation on loads exerted along the walls of silos according to amount and properties of the particulate solids to be handled. Such loads include the pressures developed during filling, storage and discharging. Classical theories are available for predicting the static pressures in silos after initial filling (Janssen, 1895; Walker, 1966; Walters, 1973 a, b; Jenike, 1961; Enstad, 1975, 1981; Rotter, 2001). It is however also a fact that such pressures may vary from one filling to another in practice(Rotter, et al, 1995; Campbell, 2006; Zhong, et al, 2001; rotter et al., 2002). The pressures on silo walls during discharging are very different from those in filling, and are generally more complex. Attempts have been made in order to produce satisfactory rules (Walker,1966 ; Walters, 1973; Jenike and Johannson, 1968; 1987; Enstad, 1975, 1981; Jenike, 1987). For example, theories that describe the pressures on silo walls are now well established in situations where a silo is in a symmetrical mass-flow discharge mode. It has long been also recognised that the loads exerted on the wall of a funnel flow silo are unpredictable. Much further work is needed before the effects of different material properties on these pressures and the mode of discharge are fully understood (Carson et al. 1991, Drescher, 1992; Cates et al., 1998; Baxter and Behringer, 1989; Rotter, 1998, 2001; Rotter et al. 1995, 2002, Jenike, 1961, 1987).

Mass flow generally is superior to funnel flow in avoiding flow disruptions and quality variations. Mounting flow aid devices is among a number of means used to influence the flow mode in order to obtain mass flow in a silo with a reasonably shallow hopper (Jenike, 1964; Johanson, 1968; Enstad, 1996). Such devices are commonly referred as inserts, like a double cone insert, a cone in cone and an inverted cone insert. Considerable efforts have been expended in finding best configurations between the inserts and silos to achieve the optimal functional results. Concerns are aroused about the effects of an insert on the loads of silo and hopper walls, and about the loads on the insert itself.

Up to now there are few experimentally proven equations for calculating the stress distributions in walls of silos and the loads on inserts. Strusch and Schwedes (1994) found that the stress state occurs between a wedge-shaped insert and a silo is similar to that in a hopper, and proposed the slice element method to calculate the loads on the insert, where mass flow is implied. Finite element calculations have been tried to predict the loads on inert, and to examine the influence of insert position on the wall stress distribution (Strusch et al, 1993; Schuricht et al. 2009).

Measurements of wall normal stresses on silos with inserts have been carried out. Measurements by Theimer (1974) and Nothdurft (1976) showed a cone shape insert increased in the wall normal stress at the level of the insert during filling and during discharging. However, Kroll (1975) observed a decrease in the wall normal stress at the level of a tied-rod insert and below it. Tuzun and Nedderman (1983) observed the presence of an wedge-shaped insert affects the wall stress distribution in different ways during filling and discharging. Scholz (1988) measured an increase in the wall normal stress at the level of the insert during filling and during discharging if an wedge-shaped insert was positioned in the vertical section of the silo; no increase was observed otherwise. Measurements carried out under symmetric conditions of silos (Kroll, 1975; Kahl, 1976; Scholz, 1988) showed that the vertical load exerted on a wedge-shape insert in silos are significantly higher than the loads which result from Janssen's formula of the vertical stress in the vertical section of a silo.

In the present investigation, experiments were carried out to measure the loads imposed on the double-cone insert by the particulate solids sand (a sort of free-flow fine sand used in construction). The insert was fitted within an axi-symmetrical scale silo with an optimal configuration (Ding, 2004; Ding et al., 2001). A concentric filling method was implemented to fill the sands into the silo, the loads developed on the wall of silos and on the insert were measured simultaneously; such loads were also measured when the silo was in discharging mode. Results thus obtained are presented. Effects of the loads on the walls of silo caused by the application of the double cone insert were experimentally addressed.

Measurement Facility

An axi-symmetrical silo and a double-cone insert

A large scale axi-symmetrical silo was designed and built with stainless steel plate (S2333, 6 mm in thickness) as shown in Figure 1. The barrel of silo was 7850 mm in height, 2500 mm in diameter; it was attached with a conical shallow hopper. The conical hopper had a 45° inclination angle, 1.2 m in height with ϕ 2500 m inlet and ϕ 100 mm outlet (see (left)).

Figure 1. A large scale axi-symmetrical silo used in the measurement

Figure 2 Positions of pressure transducers mounted to on the wall of silo (Transducer Th1to Th4 in the hopper and Tb1to Tb3 in the barrel upwards along the same generator, Tt1 to Tt4 in the same circumference under transition (counter-clockwise); Tt14 diametrical opposite of Tt3, Tt2 diametrical opposite of Tt4.(Tt 1 and Th4 denote the same transducer)

A setting –up for feeding sand into silo is shown in Figure 3. As seen, a new circular tube with (ϕ150 mm x 294) and an axi-symmetrical feeding chamber were placed concentrically on the axis of the cylindrical silo. They were used to get an enforced centre-feeding. By such an arrangement, it was expected that the silo was filled from top concentrically. Discharge was also from the centre of silo through its outlet, controlled by a valve. Both were achieved with modification and implementation of its existing solids handling system (Ding, 2004).

Figure 3 A filling unit to get an enforced concentric filling

A double cone insert was fitted into the silo, aligning with the central axis of the silo. The level at which the double cone insert located was based on the results of previous efforts of investigation of how such an insert can improve the silo discharge mode (Ding, 2004; Ding et al., 2001). A configuration of the insert and the silo is illustrated in (right), with the double cone insert's lower tip extending to the outlet. Dimensions of the insert are also shown Figure 2.

Measurement methods and its readings

The measurements included the loads measurement on the wall via pressure transducers, and those on the insert via strain gauges.

Ten pressure transducers were used in the present experiment; they were mounted to the designated positions of the silo walls (as denoted in illustration in). The pressure transducers were specially designed for silo pressure measurement. Great care was taken to ensure that the face of the interacting plate of the pressure transducer had minimum protrusion into the stored solids in silo (Härtl, et al., 2007; Wojcik, et al, 2006; Ding, 2004). The small gap between the plate of transducers and the hopper wall were sealed using silicon paste. In response to the pressures exerted, the pressure transducers generated electronic signals based on the setting up in calibrations.

Calibrations of the normal pressure were carried out carefully one by one for each transducer according to the instructions specified by the supplier (DEKA Sensor & Technologie GmbH, Germany, 2002). The maximum error was 5.3 % with installations in the present experiment; this precision was deemed acceptable.

Three identical steel plates (normal stainless steel plate with a 8 mm in thinkness) named as Plate Strains: Ps 1.Ps2, Ps3 were designed to support the double cone insert. They were welded to the wall of hopper, with an even distribution in circumference, i.e., they were located between Transducer Tt1-Tt4 (Ps1), Tt1-Tt2 (Ps2) and Tt2-Tt3 (Ps3). Strain gauges were attached to the plates. Careful calibrations, similar to the previous efforts in the pressure transducers, were carried out on the response of each gauge to vertical loads exerted. The vertical loads on the insert were therefore considered to be measured by the reading of the strain gauges.

Figure 4 An arrangement of Plate Strains Ps 1.Ps2, Ps3

Instruments Hydra and Spider (HBM measurement; Germany) were used as data loggers to register measurement results from pressure transducers and strain gauges; they were saved in a PC for the analysis later.

Particulate solids used in measurement and its properties

The particulate solids used in the experiments were sand. Sufficient amounts of sand were purchased for the measurement. It had a bulk density of 1370 kg/m^3 with a particle size ranging from 0.5 to 2 mm. When it was dry, it was free flowing; the measured repose angle was 36°. The friction angle with the wall of silo was 21.8° (μ = 0.4). The moisture in sands varied during the period of measurements with approximately 0.2%; the friction angle with the silo wall could increase to as large as 26.9° (μ = 0.51).

Experiment Measurement Results and Analysis

Experiments were carried out to measure loads on the insert and the pressure transducers for both filling and discharging. The sand was left in a state of storage for 24 hours before being discharged. To find out what effects the insert had on the loads along the walls of silos, parallel measurements were performed for comparison purposes after removing the insert from the silo.

Measurement results during filling

An amount of about 45 tonnes of sand was used to fill the silo, an equivalent of solids head in a height of 5700 - 5900 mm from the bottom of the silo. The volume of the insert could contribute slightly to differences of the solids head built up during filling. In addition, the sand fed into the silo would hit the insert first and then spread and around at the beginning of filling. It affects the filling process from the desired concentric fillings, and is different from the one in the absence of an insert. This process could last until the insert was buried.

It was observed that the development of the vertical loads exerted on the insert was rather uneven during the process of filling. The results were given in Table 1 as the loads in the plates as measured by strain gauges at the end of each filling in three parallel measurements.

As seen, the loads on each individual plate varied from onemeasurement to another, even though the same amount of sand was used, and the same filling process was implemented. One can also see that the loads on the plate Ps2 were consistently higher than the other two in all measurements, reflecting a fact of skewed piling or loading during filling. It is interesting to see, however, that the sums of loads on all plates (the total load on the insert) were rather constant; and lower than anticipated as the insert might have also been supported by the sand underneath.

Figure 5 Effect of insert on normal pressure on Tt1-Tt4 at the end of filling

Starting from the difference caused by the insert in the process of filling, the loads developed along the wall when there was an insert installed certainly would be expected to be different from those when there was no insert. Results of such measurement are presented for comparisons in Figure 5 for the normal wall pressures along a circumference just below the transition, and in Figure 6 for the normal wall pressure along the generator.

Figure 5 is the average value of normal wall pressure as measured by the transducers Tt1, Tt2, Tt3 and Tt4 in absence of the double cone insert and in presence of the double cone insert. It could be inferred therefore that an installation of an insert under the current configuration might lead to a slight increase of normal pressure at the transition level due to a small increase of the solid heads. One can also notice the unevenness of pressure distribution in circumference for both cases. It was caused by a slight skewed piling during filling as stated earlier. Such unevenness got worse in presence of the double cone insert.

Similarly, the change of piling process in the beginning of filling caused the change of stress distribution pattern. As a result, as seen in Figure 6, the effects of the double cone insert were great on the normal pressure in the hopper of the silo. One can speculate that the double cone insert would also take some loads of the solids and reduce the pressure along the walls of hopper (a dramatic decrease in fact).

Figure 6 Effect of insert on normal pressure along a generator at the end of filling

When the insert was buried, the filling process continued to fill the barrel of the silo until the end of filling, a process where the double cone insert could hardly impose effect. One can therefore see that the influence of the installation of an insert on the normal pressure was quite limited on the walls of the silo barrel (Figure 6).

Loads measurement during discharge

It has been recognised that the state of stresses developed within the particulate solids during filling undergoes a change at commencement of discharge. Such a change causes a redistribution of stress within the particulate solids, and leads to a shift of loads on the walls of the silo and on the insert accordingly. The degree and the extent of stress change are reliant on the flow mode in discharge: mass flow or funnel flow; the size and shape of moving zone if the flow is in funnel flow mode.

In the present measurement, it was observed that the discharge mode was different in presence of the double cone insert from that in absence of the double cone insert. Without the insert, the discharge was a typical pipe flow. With the presence of the double cone insert, a considerable enlargement of the moving zone was seen, the flow appeared to be an expanded funnel flow; (mass flow was not achieved though (Härtl, et al., 2007; Wojcik, et al, 2006; Ding, 2004). The normal wall pressures thus developed in those processes of discharging were measured. Results as measured at the commencement of discharge are presented in Figure 7 for the normal wall pressures along a circumference just below the transition and in Figure 8 for the normal wall pressure along the generator for both cases as in presence / absence of the double cone insert.

Comparisons as shown in Figure 7 demonstrated that the installation of the double insert led to an increase of unevenness in distribution of normal pressure at the transition level. Referred to the results as presented in Figure 6, one can also notice an increase of such pressures at the commencement of discharge from those at the end of filling. Such increases are substantial, but would be considered to be limited when compared with the maximum “switch pressures” that could have occurred if mass flow had achieved.

Figure 7 Effects of insert on normal wall pressure on Tt1-Tt4 (at commencement of discharge)

Figure 8 Effect of insert on normal pressure along a generator (at commencement of discharge)

The normal wall pressures along the generator are given in Figure 8 as measured in presence or absence of the insert. As seen, it is evident that the pressure exerted in the part of hopper immediately after the transition decreased considerably in a presence of the double cone insert. One may speculate that the insert must have taken a considerable portion of solid loads, and reduced the loads exerted directly on the hopper walls. One can also see that the effect of the double insert had very limited effect on the pressure in the barrel part of the silo.

a. The loads appeared to be rather even during discharge

b. Loads as the worst in unevenness out of four parallel measurements.

Figure 9. Development of loads on the double cone insert during discharge

Loads on the insert as measured with the strain gauges in three supporting plates are given in Figure 9 a.) and b.) as examples during the whole process of discharging. A sudden increase of loads on all three plates was observed at the commencement of discharge. It is likely to be caused by the loss of supports of the sand underneath the double cone insert.

Thereafter such loads retuned rather soon to the level as that at the end of filling. It is interesting to see that the loads were getting more even on the three plates. During the large part of the discharge process, the loads on each suppoerting plate decreased gradually, in a much slow pace thanthe heads of the solids. To the ending part of discharge, such loads reduced rapidly, and were released completely at the end of discharge.

Loads developments as such are worth further exploring. One may speculate that it could have been contributed by factors, for example, the mode the solids were discharged, the initial size of stagnant zone in the expanded funnel flow and its development during discharging, the stress distribution and stress memory history within the solids in the stagnant zone, etc.

Concluding Remarks

Measurements carried out on the large scale silo in absence / presence of a double cone insert showed that, during filling, an insert might lead to slight increases of normal pressure and its unevenness at the transition level . The effect on the normal pressure was quite limited in the barrel of the silo, with a dramatic decrease in the hopper. It is also confirmed that, during discharging, the installation of an insert, while raising only slightly the normal pressure on the wall in the barrel of the silo, increased substantially the normal pressure in a region close to the transition in the hopper, but reduced considerably such a pressure in the lower part of the hopper. It might also lead to an unevenness of distribution of normal pressure at the transition level.

The loads imposed on the insert were observed rather skewed during the process of filling; however, the sum of such loads appeared to be constant. The same loads increased with a big jump at the commencement moment of discharge, and then dropped to the level as that at the end of filling. The loads decreased gradually for a large phase of the whole discharge process, with an improvement in evenness, and unloaded rapidly at the ending part of discharge.

References

Baxter, G. M. and Behringer, R. P. 1989. Pattern formation in flowing sand, *Physical Review Letters*, 62 (24), 2825-2828.

Carson, J. W., Goodwill, D. J. and Bengtson, K. E. 1991. Predicting the Shape of Flow Channels in Funnel Flow Bins and Silos, presented at the *American Concrete Institute Convention*, Boston, Massachusetts, U.S.A, March.

Campbell, C.S., 2006, Granular material flows - An overview, *Powder Technology* 162, Issue 3 208-229.

Cates, M. E., Wittmer, J. P., Bouchaud, J. P. and Claudin, P. 1998. Development of Stresses in Cohesionless Poured Sand. *Philosophical Transactions of the Royal Society of London Series A-Mathemat*, 356(1747): P. 2535-2560.

Ding, S. 2004. Investigation of flow and pressure in silos during filling and discharging in presence of inserts", *PhD thesis*, *University of Edinburgh*, Dec.

Ding, S., Hafenbrädl, von F. O., Enstad, G. G. and Jecmenica, M., 2001. Observations on the change from funnel to mass flow in silos by means of a double core, *The 7th international conference on bulk material storage, handling and transportation*, Newcastle, Australia, Oct. 25-29.

Drescher A.. 1992. On the criteria for mass flow in hoppers, *Powder Technology*, 73, p. 251-260.

Enstad, G. G. 1975. On the Theory of Arching in Mass Flow Hoppers, *Chemical Engineering Science*, Vol. 30, pp. 1273 – 1283

Enstad, G. G. 1981. A novel Theory on the Arching and Doming in Mass Flow Hoppers, *Doctoral Dissertation, The Norwegian Institute of Technology*, Trondheim

Enstad, G. G. 1996. Investigations of the use of inserts in order to obtain mass flow in silo, *POSTEC- Newsletter 15*, P13-16.

Härtl, J., Wojcik, M., Ooi, J., Rotter, M., Ding, S. and Enstad, G. G. 2007. The influence of a cone-in-cone insert on flow pattern and wall pressure in a full scale silo, *Journal of Chemical Engineering Research and Design*, Vol 4.

Jenike, A. W. 1961. Gravity Flow of Bulk Solids, Bulletin No 108, *Utah Engineering Experiment Station, University of Utah,* Salt Lake City, Utah, October , Vol. 52, No. 29, 309 pp.

Jenike, A. W. and Johanson, J. R. 1968. Bin Loads, *Journal of the Structures Division*, ASCE, April, 94(ST4), p. 1011-41.

Jenike, A. W. and Johanson, J. R., 1969. On the Theory of Bin Loads, *Journal of Engineering for Industry,* ASME, May, Series B, 91(2), p. 339-44.

Jenike, A. W., 1961. Gravity Flow of Bulk Solids, Bulletin No 108, Utah Engineering Experiment Station, *University of Utah,* Salt Lake City, Utah, October , Vol. 52, No. 29, 309 pp.

Jenike, A. W., 1987. A Theory of Flow of Particulate Solids in Converging and Diverging Channels based on a Conical Yield Function, *Powder Technology,* 50(3), 229-236

Johanson, J. R. 1967 – 68. The placement of inserts to correct flow in bins, *Powder Technology* 1, 328-333.

Kroll, D. 1975. Untersuchungen uber die Belastung Horizontaler uganker sowie vertikaler Hangependel und Gehange durch Schuttguter in Silozellen, *Diss., Techn. Univ. Braunschweig*. Germany.

Nothdurft, H. 1976. schuttgutlasten in silozellen mit Querschnittsverengungen, *Diss. Techn. Univ. Braunschweig*, W Germany.

Rotter, J. M. 1998. Shell Structures: The New European Standard and Current Research Needs, *Thin-Walled Structures*, 31(1-3), 3-23.

Rotter, J. M. 2001. *Guide for the Economic Design of Circular Metal Silos,* Spon Press, London & NewYork

Rotter, J. M., Brown, C. J. and Lahlouh, E. H. 2002. Patterns of wall pressure on filling a square platform steel silo, *Engineering Structure* 24, 135 – 150.

Rotter, J. M., Ooi, J. Y., Chen, J. F., Tiley, P. J. and Mackintosh, I. 1995. Flow Pattern Measurement in Full Scale Silos, *Research report R95-008, Silo Research Group,* The University of Edinburgh.

Scholz, V. 1988. Untersuchungen zur Anordnung starrer coaxial Einbauten in Schuttgutbehaltern, *Diss., Wilhem-Pieck-Universitat Rostock.*

Strusch, J. and Schwedes, J. 1998. Wall stress distributions in silos with inserts, and loads on inserts, in *Silos: theory and fundamentals, ed.* by Brown C. J, and Nielsen, J., E & FN, London.

Strusch, J. and Schwedes, J., 1994, the use if slice element methods for calculating insert loads, *Bulk solids handling* 14, 505-512.

Strusch, J. Lyle, C. and Schwedes, J, 1993, The Influence on the state of stress in silos by insert, reliable flow of particulate solid 2, Oslo, Norway, 727-738.

Schuricht, T.;Fürll,C. and Enstad G. G., 2009, Experimental and Calculated Loads on “Cone in Cone” Installations, *Particulate Science and Technology* 27. 4, July, 286 – 296.

Theimer, F. 1974. Japanishe Druckversuche in Mehlsilozellen mit Nasenaulauf, *die Muhle und Mischfuttertechnik 111*, 153-159.

Tuzun, U. and Neddermann, R. M. 1985. Gravity flow of granular materials round Obstacles, 1. Investigation of the effects of inserts on flow patterns inside a silo, 325-336.; 2. Investigation of the stress profiles at the wall of a silo with inserts 337-351, *Chemical Engineering Science* 40(3)

Walke, D. M., 1966. An approximate theory for pressure and arching in hopper, *Chemical Engineering Science*, 21, p.975-997.

Walters, J. K. 1973 a. A Theoretical Analysis of Stresses in Axially-Symmetric Hoppers and Bunkers, *Chemical Engineering Science*, 28 (3), p.779-89.

Walters, J. K., 1973 b. A Theoretical Analysis of Stresses in Silos with Vertical Walls., *Chemical Engineering Science*, 28 (3), 13-21.

Wojcik, M., Härtl, J., Ooi, J., Rotter, M., Ding, S. and Enstad, G. G. 2006. Experimental Investigations of Stresses and Flow in a Full Scale Silo of axial Symmetry – with and without a Double-cone Insert, *Journal of Part. & Part. Syst. Charact*. Vol. 4.

Zhong, Z, Ooi, J. Y, Rotter, M., 2001, The sensitivity of silo flow and wall stresses to filling method, *Engineering Structure*, 23, P. 756-767.

Figure 10.

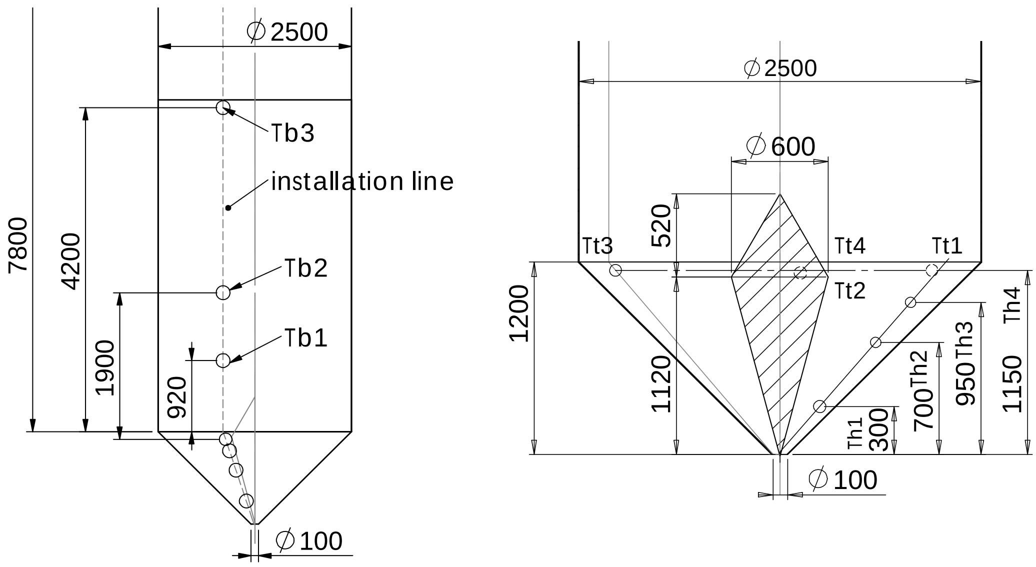


Figure 11

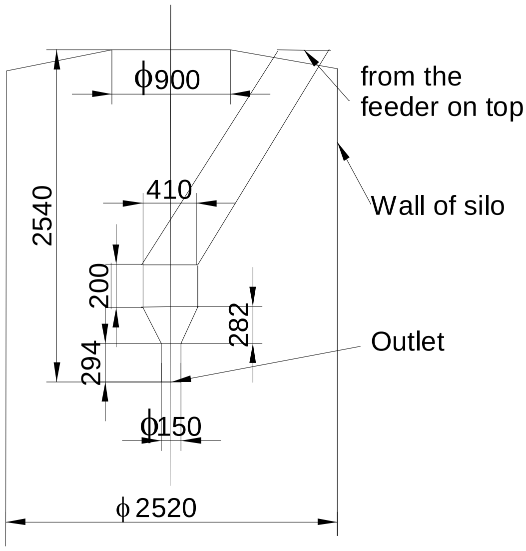


Figure 12

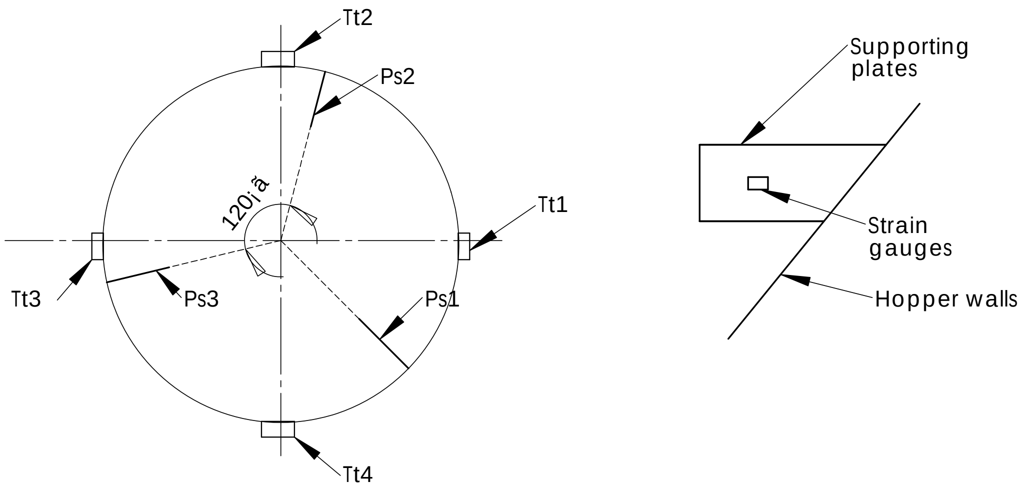


Figure 13

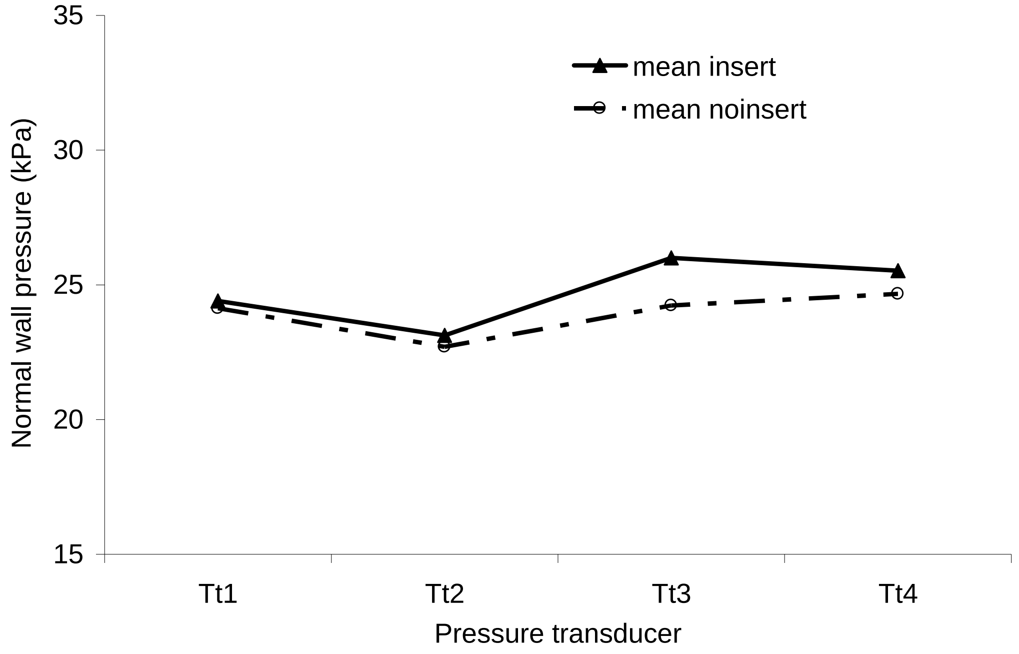


Figure 14

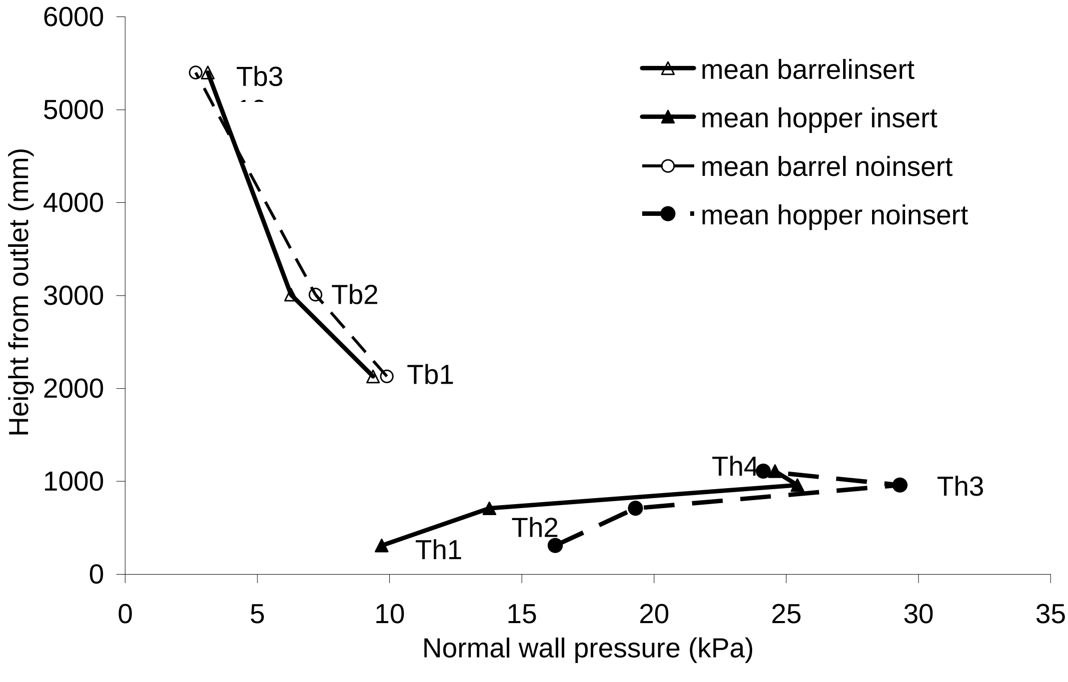


Figure 15

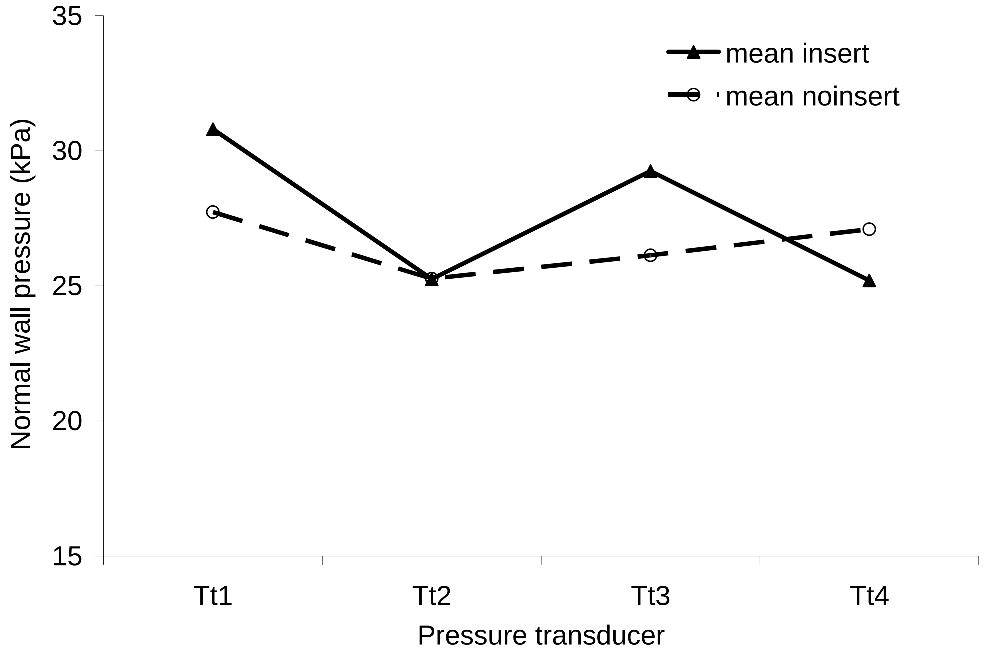


Figure 16

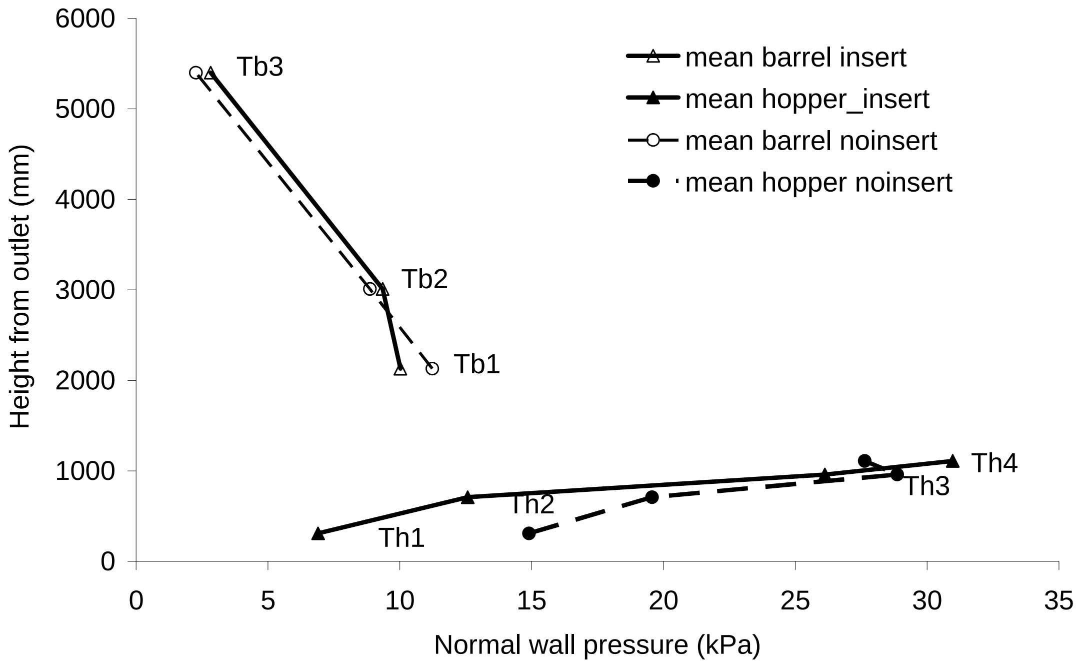
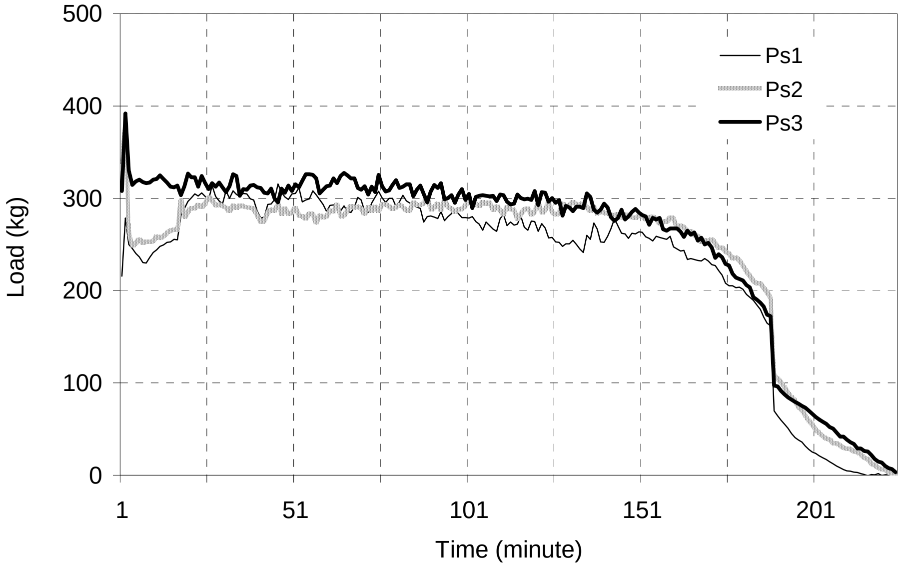
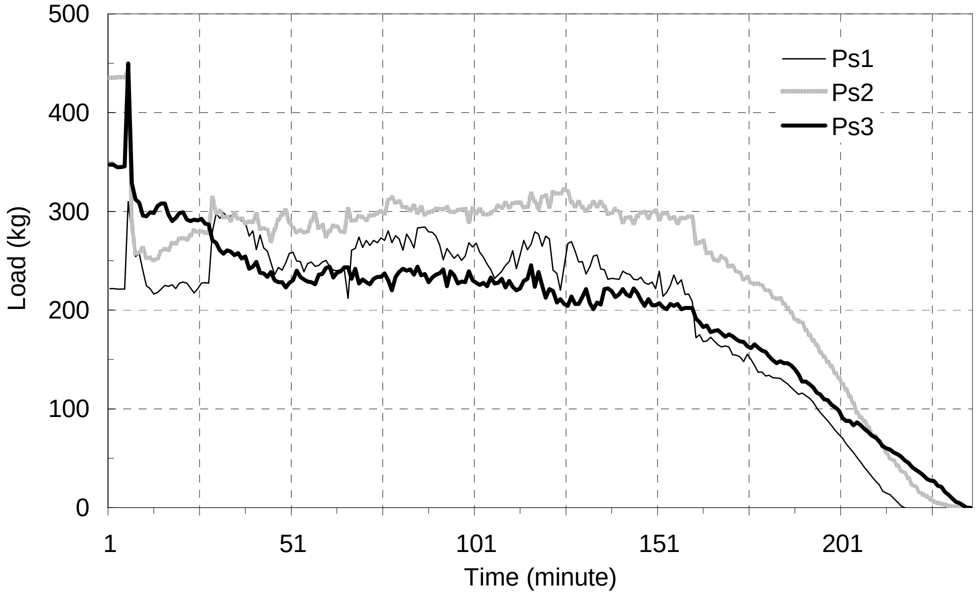


Figure 17



a. The loads appeared to be rather even during discharge



b. Loads as the worst in unevenness out of four parallel measurements.

Figure 18.