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An experimental study of a stratified thermal storage under variable inlet temperature for different inlet designs

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Abstract—This paper presents a comprehensive experimental study to evaluate the performance of a stratified tank under variable inlet temperature conditions. A new inlet design (a modified version of Davis and Bartera's inlet design) was used and compared with the two most widely used conventional inlets (side and top). The results indicate that passive devices of the kind used by Davis and Bartera and this study, offer no advantage over the conventional inlets under variable inlet temperature conditions. However, the experimental database provided in this study is invaluable to the development of computational models which are more capable in identifying the promising inlet designs for stratification enhancement in single stratified tanks.

INTRODUCTION

SOLAR ENERGY single stratified storage tanks may operate under constant or variable inlet temperature conditions. At fixed collector flow rates the latter condition is the most frequently encountered due to the intermittent nature of incident solar radiation. Under these conditions the conventional inlets, usually placed in the uppermost and lowermost parts of the tank, are known to produce severe mixing which degrades the thermal performance of the storage tank and, eventually, the solar collector. This led some investigators to search for inlet designs, which utilize the hydrodynamic and hydrostatic effects to guide the incoming flow to its proper temperature level in the storage tank. Notable design attempts of inlets of this type are those of Gari *et al.* [1], Loehrke *et al.* [2], Gari and Loehrke [3] and Davis and Bartera [4]. Further details on the effects of different inlet designs and other parameters on stratification may be found in a review paper by Hollands and Lightstone [5].

The inlet designs developed in refs. [1–3] consist of a rigid (see Fig. 1) or flexible porous manifold that removes the momentum of the incoming fluid and inhibits mixing while allowing buoyancy forces to position the fluid at the appropriate level in the tank. The published results show a comparison of the performance of the porous manifolds (both rigid and flexible) with several conventional inlets. The porous manifolds were shown to be superior to the other inlets tested. However, the tests conducted were mostly of partial charge and recycle type, i.e. the upper half of the tank was filled initially with hot water and the cold water from the bottom half was circulated back to the tank through different types of inlets.

In the experimental study of Davis and Bartera [4], two solid baffle plates placed inside the test tank at mid-height on opposite sides were spaced 5.08 cm (2 in.) from the wall (see Fig. 2). The flow from the solar collector and from the load enters the tank through two inlet ports at mid-height and impinges at the plates where it is then diverted vertically up or down depending on the difference between the inlet and local tank fluid temperatures. However, this approach was not fully explored by the investigators. The tests conducted were not comprehensive since they treated only a special case wherein the thermocline (the region between the hot and cold portions of fluid) location was already above the level of collector return water (mid-height of the tank) when the pump was turned on.

In this study the inlet design of Davis and Bartera [4] was modified and tested. The design which will be referred to as the perforated distributor, consists of a perforated circular baffle [147 cm (58 in.) high and 35.6 cm (14 in. o.d.)] with a 12.7 cm (6 in.) solid portion located about its center (see Fig. 3). The baffle was fitted inside the test tank. In order to use this inlet, the incoming flow was distributed through a distributor manifold (located on the top of the test tank) into 32 inlets located around the test tank at mid-height and impinged on the solid portion of the baffle from the outside. This was done to obtain an axisymmetric uniform flow entry into the tank. This design differs from that of ref. [4] by the use of circular baffle and the absence of load loop. Perforations were provided to reduce the entrainment of the incoming fluid by the ambient fluid as the former seeks its temperature level.

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NOMENCLATURE

H	height	T_{max}	maximum temperature
t	time	T_{min}	minimum temperature
t^*	dimensionless time, Vt/H	V	average vertical velocity.
T	temperature		

In addition, two types of conventional inlets were tested under conditions similar to those of the mid-height inlet to assess its relative performance. These are:

(1) side inlet: 1.9 cm (0.75 in.) diameter port located at 5.1 cm (2.0 in.) from the port center to the top of the tank;

(2) top inlet: 1.9 cm (0.75 in.) diameter port located at the center of the top of the tank with the flow impinging on a 35.6 cm (14 in.) diameter solid Plexiglas disk displaced 2.5 cm (1.0 in.) from the top of the tank.

EXPERIMENTAL SET-UP

The experimental set-up (see ref. [6]) used consists of an insulated water heater tank, a tap water settling tank, an insulated test tank, a catch tank (not shown), circulation and metering system, temperature sensor arrays, a data acquisition system, and a distributor manifold (see Fig. 4).

The heater tank is capable of providing hot water at any desired temperature up to 93°C (200°F). The tap water settling tank, was used to store tap water overnight to have water at approximately uniform room temperature. The water was then mixed with hot water to achieve the desired variation in the inlet temperature. The test tank is an insulated, cylindrical, commercial steel tank 0.254 cm (0.1 in.) thick wall, 0.406 cm (16 in.) diameter, 1.576 m (62.06 in.) high and wrapped with 7.62 cm (3.0 in.) fiberglass insulation. This tank consists of three parts: the bottom part [0.82 m (32.31 in.) high], the top part [0.66 m (26 in.) high], and the inlet adapter [0.1 m (3.75 in.) high]. A schematic of the test tank is shown in Fig. 5. The inlet adapter is designed to facilitate the installation of two types of inlets, the top and side inlets. The catch tank is scaled to measure the volume of fluid forced out of the test tank during the charging tests which is then used to calculate the average volume flow rate.

The temperature sensor arrays consist of 36 T-type thermocouples mounted in nine levels with four thermocouples at each level extending 20.32, 10.16, 5.08 and 1.27 cm (8.0, 4.0, 2.0 and 0.5 in., respectively) inside the test tank (see Fig. 5). Four additional

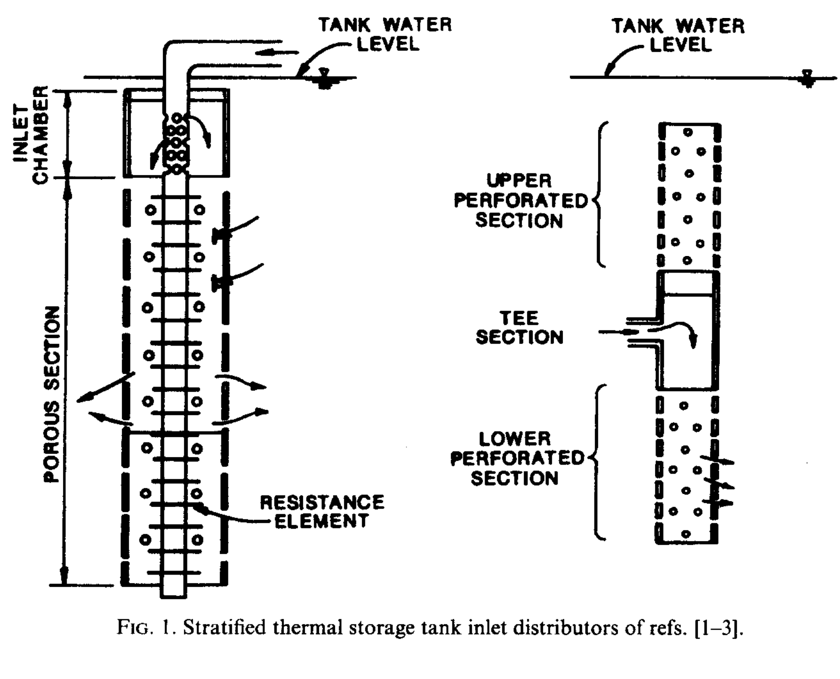

FIG. 1. Stratified thermal storage tank inlet distributors of refs. [1–3].

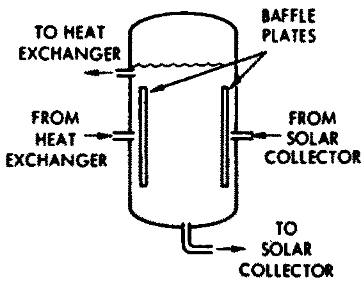

FIG. 2. Inlet configuration used by Davis and Bartera [4].

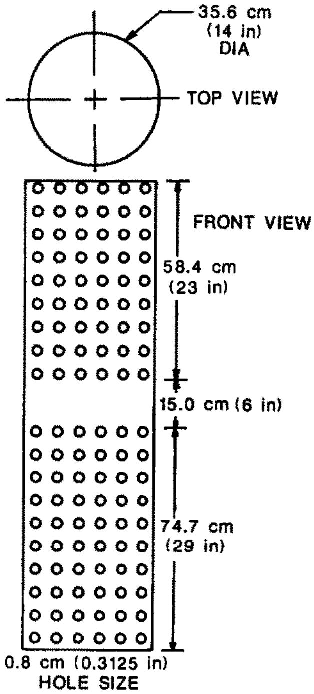

FIG. 3. Perforated baffle.

thermocouples were used to measure the inlet, outlet, hot and tap water temperatures. The data acquisition system was a Monitor Labs 40-channel data logger interfaced with a TI professional computer. The transient temperature readings were collected at time intervals from 20 to 75 s depending on the flow rate. Calibration of the thermocouples indicated the accuracy of temperature measurements which was within $\pm 0.55°C$ ($1.0°F$).

The distributor manifold, located on top of the test tank, distributes the incoming flow into 32 pipes connected to the test tank at approximately mid-height and spaced equally around the circumference of the test tank. This arrangement was chosen to distribute the incoming flow evenly as it impinges on the solid portion of the baffle from the outside.

The tests covered a wide range of conditions, i.e. flow rates and temperature variations. Duplicate tests were conducted with the two conventional inlets, the top and side inlets, to measure the relative performance of the new inlet design. The tests were restricted to the charge mode of operation since it is doubly important for both solar collectors and storage tanks. In these tests the transient inlet temperature profile was selected first and the flow rates of hot and tap water were calculated so that when mixed together, they would produce the desired inlet temperature.

RESULTS AND DISCUSSION

Figures 6–8 show the transient temperature profiles monitored at nine elevations in the test tank for the side and top inlets and the perforated distributor, respectively. The transient inlet and outlet temperature profiles are also shown. In the following dis-

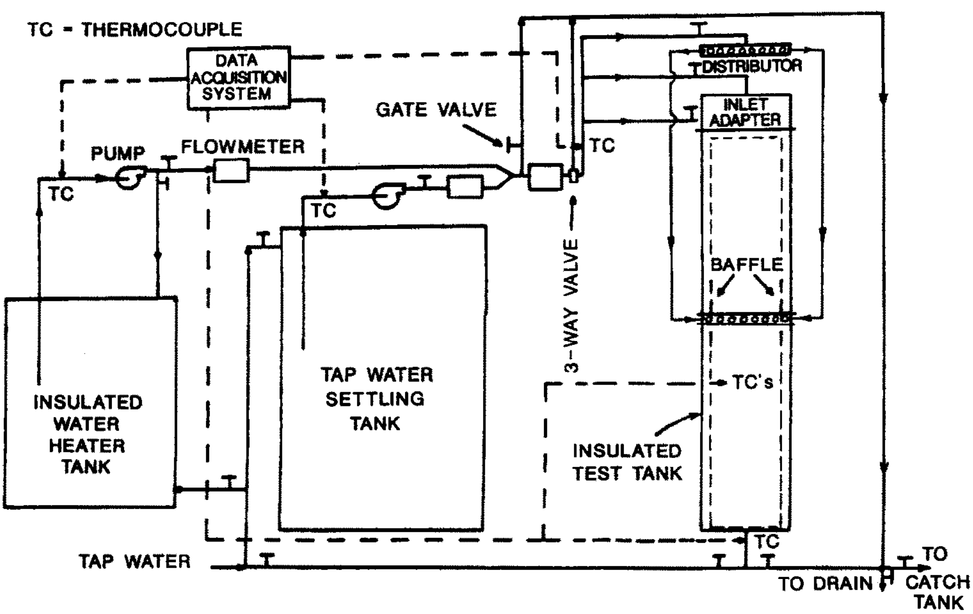

FIG. 4. Schematic of the experimental set-up.

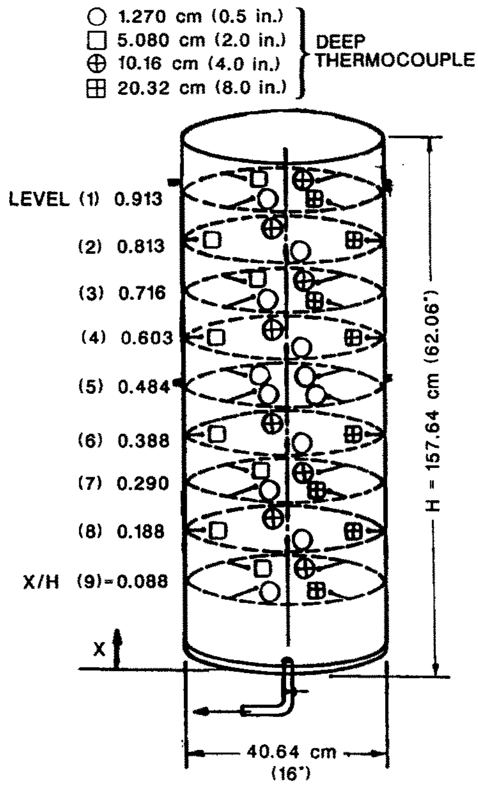

Fig. 5. Thermocouple locations inside the test tank.

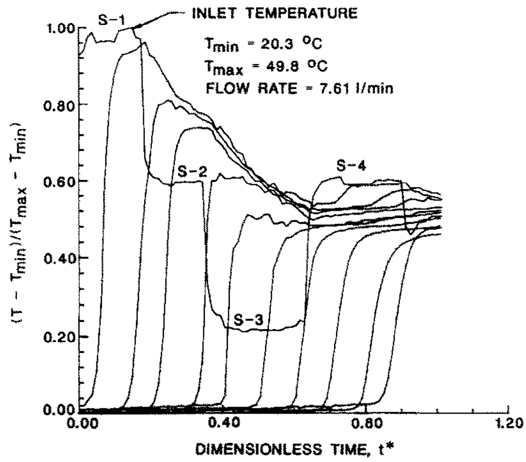

Fig. 7. Transient temperature profiles under variable inlet temperature condition (top inlet; run No. 33 of ref. [6]).

cussion reference will be made to the regions of step change (minor step changes are ignored) in the inlet temperature as S-1 for the first step, S-2 for the second step and so on.

The transient temperature response to the first step in the inlet temperature (S-1) is seen to be a function of the inlet configuration used. While the responses for the side and top inlets are similar in character (see Figs. 6 and 7), there is a quantitative difference among them, and also they both differ from that of the perforated distributor (see Fig. 8). Observing the temperature response to S-1, it can be seen that the side inlet causes more mixing than the top inlet. This is evident, since the maximum temperature reached at the first level is less for the side inlet than for the top inlet. In fact, the first three levels for the side inlet have responded to S-1 while only the first two levels have responded in the case of the top inlet. This is indicative of the extent of mixing caused by the two inlets considered. Before leaving the S-1 region, observation of the response for the case of perforated distributor gives a rather different picture. The first five levels responded to S-1 almost simultaneously. The sixth level, although later in time, has also responded to S-1. This indicates that severe mixing is taking place in a large portion of the tank.

While flow visualization tests could not be performed in the test tank, the computer simulations (see refs. [7, 8]) have provided the explanation for this behavior. That is, the hot fluid flowing in the annulus between the perforated baffle and the tank wall entrains cold fluid from the upper half of the tank.

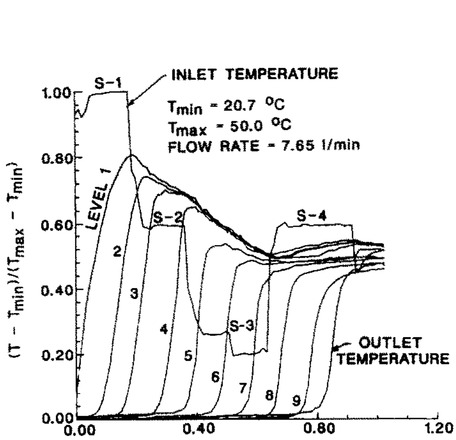

Fig. 6. Transient temperature profiles under variable inlet temperature condition (side inlet; run No. 30 of ref. [6]). Levels ordered as in Fig. 5.

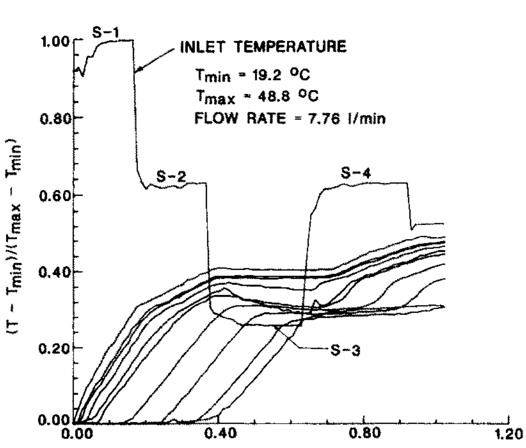

Fig. 8. Transient temperature profiles under variable inlet temperature condition (perforated distributor; run No. 22 of ref. [6]).

This leads to setting up localized recirculation zones which in turn enhance mixing greatly.

The second step change in temperature (S-2 in Figs. 6–8) is seen to produce severe mixing, extending through the first four levels in the tank for both cases of side and top inlets. Again it is observed that the mixing is more severe in the case of the side inlet compared with the top inlet. At the end of S-2, the first four levels, in the case of side inlet, have essentially the same temperature (see Fig. 6) while for the top inlet, only the first three are fully mixed (see Fig. 7). A further decrease in the inlet temperature (step S-3), causes the tank to be essentially fully mixed. It should be noted that in the S-3 step, while the inlet temperature has dropped below that of the first four levels (see Fig. 7), the temperature in these levels did not drop at the same rate. This indicates that the incoming fluid, possessing a negatively buoyant force, slips down to the level where neutral buoyancy is encountered and displaces the fluid layer there. This is evident from the temperature history of the different elevations in the tank (note the leveled parts of the temperature profiles).

Turning to Fig. 8 for the perforated distributor, it is seen that the step change in temperature (S-2) was immediately felt by the bottom half of the tank, particularly by level 7 and later by level 8. It should be noted that this warming up of the lower part of the tank is not justified on the basis of buoyancy force arguments since the inlet temperature (S-2) is still much higher than that of the bottom of the tank. The only justification is that advanced earlier in this section regarding the entrainment and the subsequent development of recirculation zones which have an adverse effect on stratification. Slight warming of the upper half of the tank is observed (see Fig. 8). As the inlet temperature dropped, as in step S-3, the temperature of both level 9 and the outlet responded without any time lag. This indicates that the flow is short-circuiting to the outlet, causing a single large recirculating zone in the bottom half of the tank which results in the bottom half of the tank becoming fully mixed while the upper half maintains the same prestep temperature distribution. Another method comparing the performance of the different inlets was to conduct special tests of partial charge and recycle similar to the experiments of refs. [1, 2]. In these tests, initially the top half of storage tank was full of hot water and the bottom half full of cold water. After creating this initial stratification inside the tank, cold water was pumped in for about an hour at a rate of 3.78 l $\min^{-1}$ (approximately one tank volume was replaced). The process was repeated for all three inlets and the results in terms of temperature vs tank height at different time steps are presented in Figs. 9–11. Figures 9 and 10 for the side and top inlets show that the initial stratification inside the test tank gets disturbed very quickly and after about 33 min the tank becomes fully mixed. However, Fig. 11 for the perforated distributor indicates that the storage tank has approximately maintained its initial stratification the whole hour long. Comparison of our results with those of Loehrke *et al.* [2] indicates that our results for the conventional inlets are comparable with theirs. However, the performance of the perforated baffle used in this study seems to produce less mixing (better stratification) than their porous manifold.

In view of the above results, a question arises

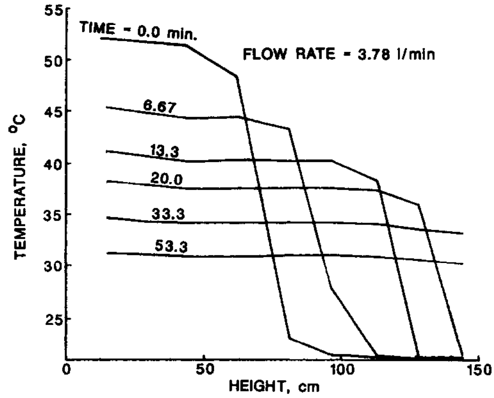

FIG. 9. Transient temperature profile during partial charge and recycle test (side inlet).

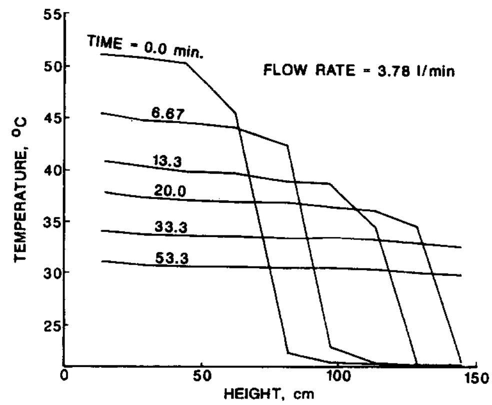

FIG. 10. Transient temperature profile during partial charge and recycle test (top inlet).

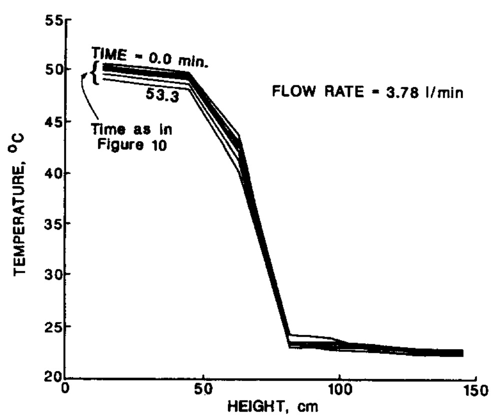

FIG. 11. Transient temperature profile during partial charge and recycle test (perforated distributor).

regarding the performance of different inlets under the variable inlet temperature condition. Since engineering designs cannot be judged based on a single performance test, a measure of performance had to be devised. Observing that the final objective of stratification enhancement is to improve solar collector efficiency, the collector efficiency was chosen as an index of performance. This is done by using the transient tank outlet temperature profile as an input to a solar collector model and calculating the solar collector efficiency. Comparison of the efficiencies obtained for different inlets gives the relative performance. However, this procedure may be perfectly justified when the conditions of the experiments are identical from one experiment to the next. The results shown in Figs. 6–8 show that this is difficult to achieve. Some variations in the inlet temperature profiles or in the flow rates will undoubtedly occur. Therefore, it was decided to devise a reference measure in addition to the one described above. That is, the tank outlet temperature profiles calculated based on the fully mixed model were also fed into the solar collector model and the collector efficiency is calculated. This represents the lower limit since the fully mixed case is the worst condition possible. On the other hand, the other extreme condition of interest is that of a fully stratified case. That is, the flow seeks its temperature level without mixing throughout the path. However, mixing with the adjacent layers is allowed. These happened to be the conditions modeled by Sharp [9]. The computer code based on Sharp's model (see ref. [10]) was implemented and the calculated tank outlet temperature profile was used in a similar manner to that for the fully mixed model. The solar collector model based on the theory of flat plate collector of Hottel and Whillier presented by Duffie and Beckman [11] is described in ref. [6].

Figure 12 shows the tank outlet temperature profiles calculated by the fully mixed and the fully stratified models compared with the experimental profile which corresponds to the experimental data of Fig. 7 for the top inlet. The inlet temperature profile is also shown. The corresponding instantaneous collector efficiency profiles are shown in Fig. 13. It is seen that the collector efficiency based on the experimental results falls between the two profiles corresponding to the fully mixed and the fully stratified cases. However, it is closer to the fully stratified behavior. Figures 14 and 15 are analogous to Figs. 12 and 13, respectively, and correspond to the experimental conditions of Fig. 8 for the perforated distributor. The experimental and fully mixed tank outlet temperature profiles cross at $t = 13$ min (see Fig. 14) which corresponds to $t^* = 0.5$ in Fig. 15. The higher temperature observed experimentally compared with that predicted by the fully mixed model proves the suggestions made earlier in this section about the short-circuiting phenomenon observed when examining Fig. 8.

Integration over the time of the collector efficiencies shown in Figs. 13 and 15 (based on the experimental data) shows that the perforated distributor offers no advantage over the conventional top inlet (0.80 for

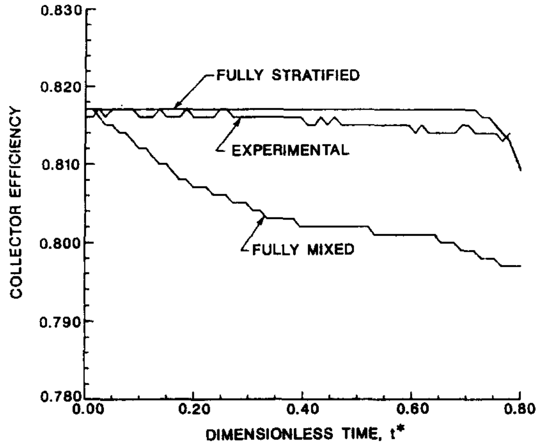

Fig. 13. Solar collector instantaneous efficiency calculated based on outlet temperature profiles of Fig. 12 (top inlet).

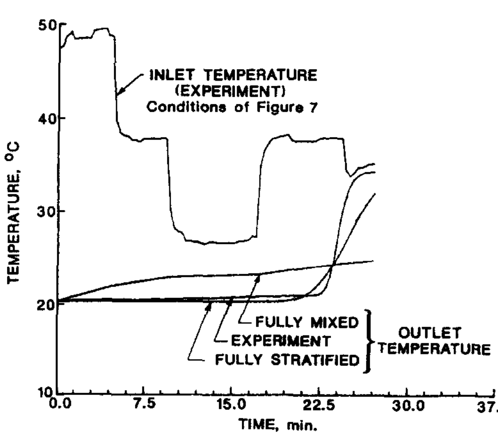

Fig. 12. Thermal storage tank transient inlet and outlet temperature profiles (top inlet).

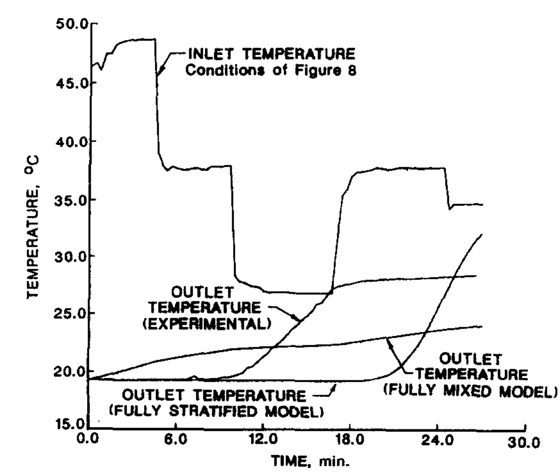

Fig. 14. Thermal storage tank transient inlet and outlet temperature profiles (perforated distributor).

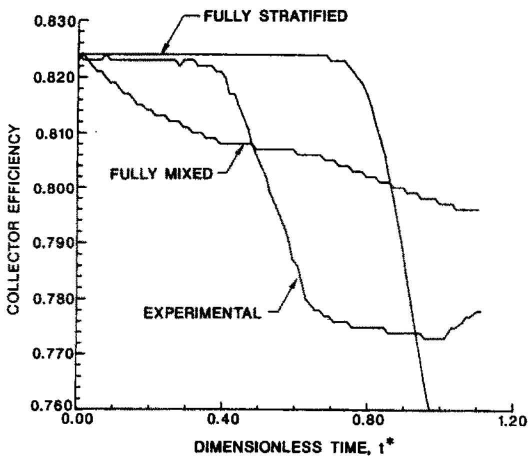

FIG. 15. Solar collector instantaneous efficiency calculated based on outlet temperature profiles of Fig. 14 (perforated distributor).

the distributor vs 0.815 for the top inlet). A similar trend was observed with the rest of the experimental runs. Therefore a similar conclusion may be stated about the inlet design of Davis and Bartera [4]. It should be pointed out that the influence of stratification on system performance is probably more subtle than implied by Figs. 13 and 15 and a full system simulation would render a more accurate evaluation.

CONCLUSION

A single stratified tank used for solar thermal energy storage frequently operates under variable inlet temperature conditions due to the intermittent nature of incident solar radiation. In this study comprehensive experiments with a new inlet design (perforated distributor) were conducted. The performance of this new inlet design was compared with that of two conventional inlets most widely used in a single stratified tank, i.e. the side and top inlets. The results indicate that passive devices of the type used in this study or in the study of Davis and Bartera [4] may not be very effective promoters of stratification in thermal storage tanks under variable inlet temperature conditions. However, in view of the limited experimental data available in the literature with variable inlet temperature conditions, the tests conducted in this study contribute in enlarging the database. This should serve in the development of analytical models and simulation programs which are more capable of identifying the promising inlet designs for enhancement of stratification in thermal storage tanks and better utilization of solar energy thereafter.

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UNE ETUDE EXPERIMENTALE DU STOCKAGE THERMIQUE STRATIFIE DANS DES CONDITIONS VARIEES DE TEMPERATURE ET DE GEOMETRIE D'ENTREE

Résumé—On présente une étude expérimentale pour l'évaluation des performances d'un réservoir stratifié sous des conditions variables de température d'entrée. Une nouvelle conception de l'entrée (une version modifiée de celle de Davis et Bartera) est utilisée et comparée avec celles plus largement utilisées (latéralement et sommet). Les résultats montrent que les montages passifs du type préconisé par Davis et Bartera et par cette étude, n'offrent pas d'avantages par rapport aux entrées conventionnelles pour des conditions de température d'entrée variable. Néanmoins les données expérimentales sont inestimables pour le développement des modèles de calcul qui sont plus capables d'identifier des conceptions d'entrées promotteuses pour l'amélioration de la stratification dans les réservoirs.

EXPERIMENTELLE UNTERSUCHUNG EINES GESCHICHTETEN THERMISCHEN SPEICHERS BEI VARIABLER EINLASSTEMPERATUR FÜR UNTERSCHIEDLICHE EINLASSKONSTRUKTIONEN

Zusammenfassung—Es wird eine umfassende experimentelle Untersuchung vorgestellt, die zur Bewertung der Leistungsfähigkeit eines geschichteten Speichers bei variablen Einlaßtemperaturen dient. Eine neue Einlaßkonstruktion (modifizierte Version der Einlaßkonstruktion von Davis und Bartera) wurde mit den am weitesten verbreiteten konventionellen Einlaßvorrichtungen (seitlich und oben) verglichen. Die Ergebnisse weisen darauf hin, daß die passiven Vorrichtungen derart, wie sie von Davis und Bartera und in dieser Untersuchung benutzt wurden, keinen Vorteil gegenüber konventionellen Einlaßvorrichtungen bieten, wenn variable Einlaßtemperaturen vorliegen. Die in dieser Untersuchung vorgestellte Datenbasis ist jedoch nützlich für die Entwicklung von Computermodellen, die besser geeignet sind, die vielversprechenden Einlaßkonstruktionen für eine Verbesserung der Schichtung in einfach geschichteten Behältern zu identifizieren.

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ СТРАТИФИЦИРОВАННОГО ТЕПЛОВОГО АККУМУЛЯТОРА ПРИ ИЗМЕНЯЮЩЕЙСЯ ТЕМПЕРАТУРЕ НА ВХОДЕ И РАЗЛИЧНЫХ КОНСТРУКЦИЯХ ВХОДА

Аннотация—Проводится экспериментальное исследование с целью оценки рабочих характеристик стратифицированного аккумулятора при изменяющихся температурных условиях на входе. Использовался вход новой конструкции (модифицированный вариант конструкции Дэвиса и Бартера), который сравнивался с двумя наиболее распространенными входами (боковым и верхним). Результаты показывают, что пассивные устройства типа используемых Дэвисом и Бартером, а также рассмотренные в настоящем исследовании не имеют преимуществ по сравнению с обычными входами при изменяющихся температурных условиях на входе. Однако полученная база экспериментальных данных является неоценимой при разработке вычислительных моделей, которые наиболее пригодны для определения перспективных конструкций входа, увеличивающих стратификацию в единичных стратифицированных аккумуляторах.