A RECIRCULATING OVEN FOR ATOMIC BEAM FREQUENCY STANDARDS*

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Summary

This paper describes a simple recirculating oven which produces an atomic beam which can be better collimated than that from a conventional oven with equivalent collimation ratio. The oven is spill proof and requires only modest power for operation. Under suitable conditions the total beam flux can be significantly less than for conventional cesium ovens. This translates into more efficient use of the cesium charge and less contamination of the beam tube.

Introduction

While high intensity molecular beam sources have been advanced considerably during the past several decades, the basic design of the lower intensity sources for atomic beam (cesium) frequency standards have remained largely fixed. This reflects the fact that such sources have performed well and development work has naturally focused on other aspects of the systems. However, recent demands for standards of higher reliability, longer life, more rugged design, and lower power consumption have caused us to take another look at the beam source and to ask whether design improvements can materially affect any of the performance factors mentioned above. This question led us to the study of a rather simple recirculating oven which departs significantly in design from conventional ovens. While adequate life tests will require more time, performance tests show the oven to have excellent collimation characteristics which bear on both tube contamination and efficiency of use of the cesium charge.

The present design of the oven involves one significant disadvantage: the forward end of the oven must be kept at a temperature near the melting point of cesium to minimize the off-axis flux. It appears that design modifications can ameliorate this disadvantage, but such modification is only conceptual and remains to be demonstrated.

The concept for recirculation in an atomic beam source is not new [1,2]. What we introduce here is a particularly simple implementation of the recirculation concept which also yields a very narrow beam profile as well as several other advantages.

The on-axis flux in atomic beam ovens depends primarily on the source vapor pressure. It is the control of the off-axis flux which differentiates three classes of ovens (underlined below). Ideally, the collimation of the beam should involve simple geometric shadowing, that is, the collimator should just cut off the source emission in undesirable directions. However, it is difficult to achieve this end without introducing certain undesirable characteristics. For example, a carbon collimator can be used to absorb every cesium atom which strikes it, thus achieving the desirable end, but the carbon soon saturates and the cesium deposited on the walls is either re-evaporated or, if it sticks, causes a change in the size or shape of the collimator. This type of oven, which we call a dark-wall oven, demonstrates a key problem in oven design, that is, dealing with the flux which strikes the walls of the collimator.

Conventional ovens use arrays of long narrow tubes to achieve good collimation. The array of narrow tubes allows for higher beam flux and for a good length-to-diameter (collimation) ratio in a short oven. To prevent these tubes from building up deposits of cesium, they are maintained at an elevated temperature and atoms which strike the wall are then re-evaporated with a $\cos(\theta)$ distribution (θ is the angle with respect to the normal to the surface) [3]. This re-emission from the walls broadens the beam profile well beyond that produced by dark-wall ovens [4], but such ovens have nonetheless proven to be very workable in cesium standards. Because all cesium is eventually re-emitted from the walls, we call this type of oven a bright-wall oven.

The recirculating oven described in this paper captures the flux which strikes the collimator walls and returns it through capillary action for re-use by the source. Of course, these walls are saturated with cesium and emit atoms with a $\cos(\theta)$ distribution also, but at a rate which is commensurate with the vapor pressure and temperature at each point on the wall. This emission rate is not a function of the rate of arrival of atoms at the wall, but can be greater or less than that rate depending upon the temperature of the wall. With certain precautions the beam profile from such an oven can be made significantly narrower than that of a bright-wall oven with the same collimation ratio and on-axis intensity, and the integrated emission can be considerably smaller.

Recirculating Oven Design

The recirculating oven is shown schematically in Figure 1a. The entire structure is fabricated of a porous matrix (tungsten or molybdenum) filled with the source liquid (cesium for our case). The forward-facing surface at the source temperature T_2 emits a flux which is collimated by the tube whose temperature varies linearly between this source surface and the front end which is held at a temperature T_1 just above the melting point of cesium (301.5 K). Flux striking the walls is drawn into the porous material and returned to the source region by capillary action. As noted above, any element of the wall will radiate flux at a rate which is commensurate with the wall temperature and the associated vapor pressure at that temperature. The relative merit of the

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recirculating oven thus depends on the relationship between the vapor-pressure profile along the recirculating-oven walls and the same profile for the bright-wall oven. This issue is addressed in the next section.

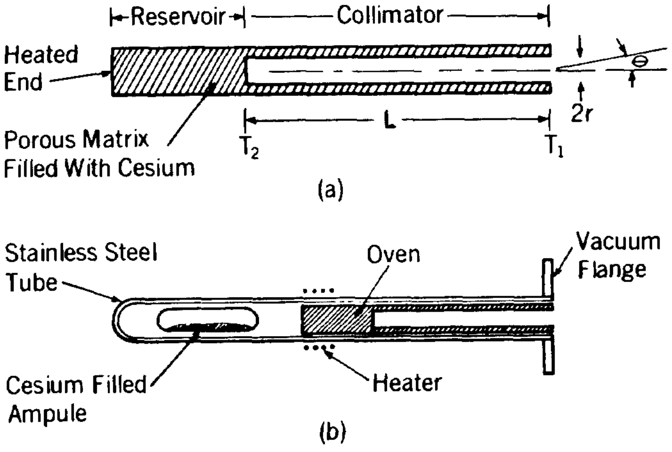

Figure 1. a) Schematic of a recirculating oven. The parameters shown are those used in the calculations. The interior end surface (at the temperature T_2) is the primary source of useful beam flux. b) Simple arrangement for filling and using the recirculating oven. With the heater energized, the cesium ampule is broken by crimping the tube and the liquid metal is absorbed into the porous matrix.

Figure 1b shows the particularly simple experimental arrangement which we have used to mount and charge the porous-tube ovens for performance and life tests. The cesium charge is introduced into the porous matrix by breaking the ampule (crimping the stainless tube) while heating the whole system so that the cesium is molten. The volume of cesium in the ampule is kept just below the volume of the void space in the oven matrix. This assures that all of the cesium (when drawn into the porous matrix) is bound by capillary force and the oven is then "spill-proof". The simple arrangement for mounting the oven has one significant drawback. It does not provide for easy access for measurement of the oven temperatures. T_1 is probably very near the temperature of the vacuum flange to which it is attached, but the temperature along the tube adjacent to the heater places only an upper bound on the temperature T_2. T_2 is most likely lower and we will treat it as an adjustable parameter, although we require that it be close to and bounded by the temperature adjacent to the heater.

The collimator for the particular recirculating oven described in this paper has an internal diameter (2r) of 2 mm. Several ovens of the shape shown in Figure 1a were constructed, but the one described in this paper has different diameter reservoir and collimator sections. The collimator length L is 4.5 cm and the approximate outside diameter is 2.5 mm. The oven was fabricated in 2 pieces. The reservoir is a solid, porous cylinder of diameter 5.3 mm and length 1.3 cm with a short hole in the center of one end which provides for an interference fit with the collimator tube. The collimator is porous, 80%-dense tungsten and the reservoir, also tungsten, is 50% dense.

An important consideration in the final design of an oven of this type is the distribution of cesium within the matrix. Ideally, as the cesium is depleted, the source surface and collimator should remain saturated with the liquid. With careful design it appears that this can be achieved. Where a temperature gradient exists in this capillary matrix, there is a force on the contained liquid in a direction opposite to the gradient, that is, the liquid is forced from the hot toward the cold region. With proper reservoir design and heater placement, the source and collimator can be made to be the last oven portions to "dry out" and the oven output should be quite flat to this point.

Modeling of Performance

The simple concepts used here to model performance are drawn from Ramsey [3] and Giordmaine and Wang [4]. The latter reference develops descriptions of the beam profiles for both dark-wall and bright-wall ovens. The profile for the recirculating oven can be obtained through suitable modification of their equation (16) which describes the emission from each element of the oven wall. The important distinctions between the three classes of ovens (dark-wall, bright-wall and recirculating) involve assumptions about wall emission and these should be restated.

1. Dark-Wall Oven - The assumption for a dark-wall oven is simple: Every atom which strikes a wall is absorbed (no re-emission).

2. Bright-Wall Oven - As stated earlier the atoms which strike the wall in a bright-wall oven are re-emitted with a cos(θ) distribution. For a collimator of uniform cross section this process of absorption and re-emission of atoms leads to a vapor pressure which varies linearly between the pressure at the source and zero at the emitting end of the tube [4]. If position along the tube is measured relative to the forward end, then the rate at which atoms are emitted from a wall-surface element at a distance z from the end of the tube is proportional to z. This assumption is not strictly valid at the front of the tube where an end correction should be made, but it seems to provide a good description of the central portion of the beam profile [4]. Some caution should be exercised in applying the model to the prediction of total oven emission since a large part of the total is emitted at large angles where the front end of the oven is important.

3. Recirculating Oven - The vapor pressure of cesium at each point along the wall of a recirculating oven is taken to be consistent with the temperature at that point on the wall. Nesmeyanov [5] gives an exponential form for vapor pressure as a function of temperature which seems to fit the vapor pressure data quite well and is convenient for performing the calculations on the recirculating ovens. In calculating the flux emitted by a wall element, the mean velocity of the atoms emitted by the wall must be

included. This velocity is proportional to the square root of the temperature of the wall [3]. For the simple uniform tube of figure 1a, the temperature can be assumed to vary linearly between T_1 and T_2.

Following the assumptions outlined above (in 3) the beam intensity as a function of the angle θ can be written as

$$I(\theta) = Ka^2\cos(\theta)[p(T_2)/(T_2)^{1/2}] \times [\cos^{-1}(Ls) - Ls(1 - L^2s^2)^{1/2}] + Ka\sin(\theta)\int_0^u [p(T)/(T)^{1/2}]\,[1 - z^2s^2]^{1/2}dz.$$

where $K = 1.458 \times 10^{23}\ m^{-2}s^{-1}$ is a constant (including Planck's constant and the mass of the cesium atom), a is the tube radius, p(T) is the pressure as a function of temperature [5], $T = T_1 + z(T_2 - T_1)/L$, L is the length of the collimator, $s = \tan(\theta)/2a$ and the upper limit u of the integral depends on the interval of θ that is considered. For $\theta < \tan^{-1}(2a/L)$, $u = L$ and for $\tan^{-1}(2a/L) < \theta < \pi/2$, $u = 2a/\tan(\theta)$. The intensity is in units of atoms/second/steradian and all other quantities are expressed in SI units. The first term of the expression gives the contribution from the source at T_2 which is just the dark-wall-oven result and the second term describes the emission from the walls. The equation is integrated numerically to compare with the experimentally determined beam profiles and a second integration over all solid angles in the forward hemisphere yields the total flux emitted by the oven.

Experiment

The beam profile for the recirculating ovens was determined using a scanning apparatus which consists of a fixed hot wire detector with a 1 mm^2 aperature at a distance of 55.2 cm from the oven, the axis of which can be tilted up to ~ 5° to either side of alignment with the detector. With this apparatus, beam profile can be determined with a relative precision (resolution) of a few percent. The absolute accuracy of the intensity measurements is approximately 10%. With the half-meter source/detector separation and the 1 mm^2 detector area, the system averages the beam flux over an angle of about 0.1° yielding an angular resolution which is more than adequate for the present studies. A dark-wall oven was constructed using a carbon collimator and the peak intensity and profile agreed well with that predicted by the dark-wall theory providing confidence in the measurement methods. While the ovens could be scanned in two directions (tilted about two axes), their cylindrical symmetry always resulted in essentially identical results, so scanning was normally performed along only one of the axes.

Results

Figure 2 shows the peak beam intensity (on-axis flux) of the recirculating oven as a function of source temperature compared with theory. This peak intensity depends only on the source temperature as long as the mean free path in the beam is long compared to any of the oven dimensions. The saturation at higher temperatures might appear to result from cesium-cesium collisions within the source since the decrease in mean free path with increasing pressure should eventually limit the beam flux. However, as will be described below, the experiments do not support this interpretation.

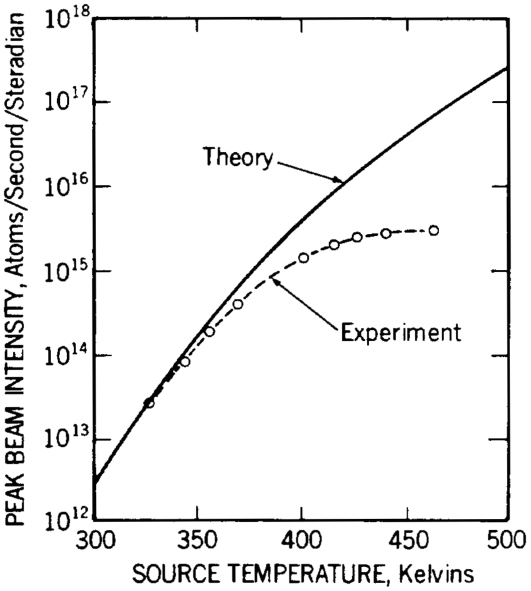

Figure 2. Peak beam intensity as a function of source temperature. The data is for the oven described in the text (r = 1 mm and L = 4.5 cm). The peak beam intensity should depend only on the source temperature.

Figure 3 shows the measured beam profile compared with the predictions of theory for the dark-wall, bright-wall and recirculating ovens. The source temperature in the recirculating-oven theory was adjusted to give the best fit to the experiment and the dark-wall and bright-wall theory then used the same source temperature. The temperature for this best fit was 14 K below the temperature measured adjacent to the heater. This was consistent with the discrepancy between theory and experiment in figure 2. No correction for the detector angular resolution of ~ 0.1° was made although, if included in the theory, this correction would not quite round off the peak enough to bring complete agreement between theory and experiment in the central region.

In an attempt to determine the mechanism for the saturation observed in figure 1, we measured the beam profile with the source at 405 K, a temperature which is well into the saturation region. If the saturation were produced by collisions in the vicinity of the source, then the effective emitting surface would be displaced forward and the collimation would not be as good, that is, the beam profile would be broadened [4]. Our measurements showed no such broadening, so the saturation must arise from another cause. We will speculate on this effect in the next section.

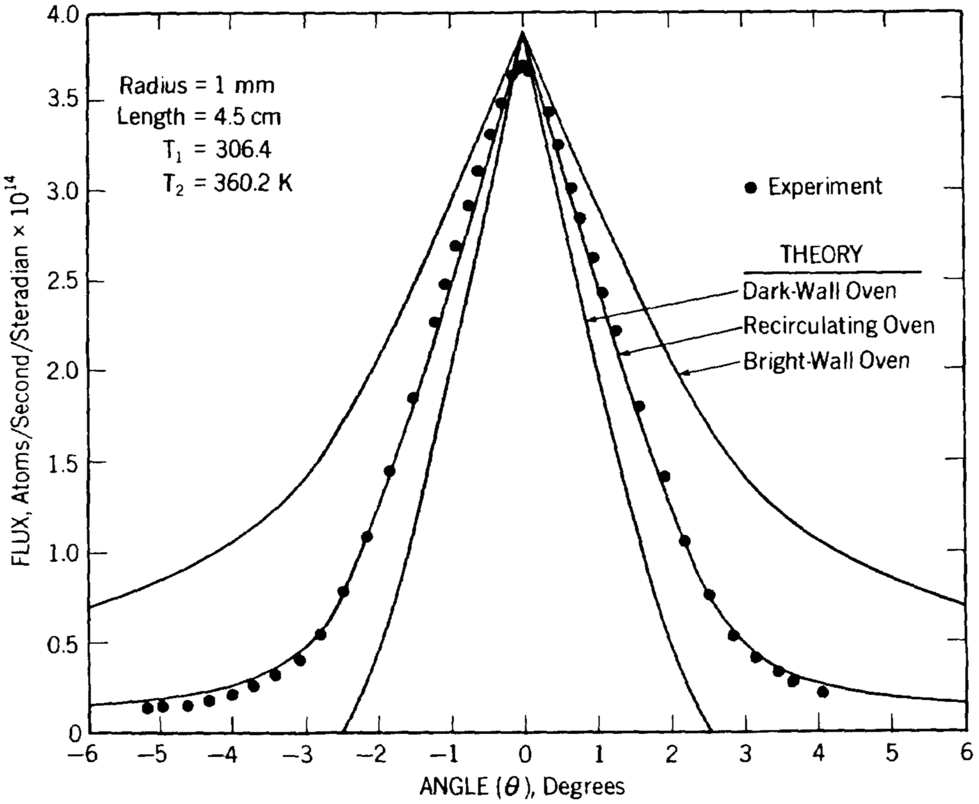

Figure 3. Beam profile for three types of ovens. The experimental points are for the recirculating oven described in the text. The parameters in the upper lefthand corner refer to Figure 1a.

To test the hypothesis that the cesium is bound by capillary action in the porous matrix, the oven was operated vertically (emitting upward and downward) as well as horizontally. Within our experimental resolution of 2% we found no change in peak beam intensity. With the oven pointing downward we would have expected problems with the detector if cesium had spilled onto it. In simple experiments performed in a sealed glass tube, the cesium charge was found to be fully absorbed by the porous matrix, so these results were not unexpected.

The oven described in this report has been operating continuously for more than six months with no appreciable decrease in emitted flux. This is not a particularly significant test of the lifetime of this type of oven, but it lends support to the idea that cesium is effectively expended from the reservoir, not the collimator or source surface. The oven was not designed with maximum lifetime as a major consideration, so, while we will keep it on life test, it will be important to address life testing with another oven.

Discussion and Conclusions

The good agreement between experiment and theory for the beam profile measurements suggests that the model and assumptions upon which it is based are reasonable. The peak beam intensity as a function of temperature is reasonably consistent with theory in view of how that temperature was measured, so one can also conclude that the experiment and theory are in accord with regard to the magnitude of the peak intensity.

The discrepancy between actual and measured source temperature is most likely due to a modest thermal resistance between the stainless steel tube and the oven reservoir. It is possible that this thermal resistance also plays a role in the "saturation" effect in figure 2. As noted in the previous section, this might appear to be a mean-free-path effect, but the beam-profile measurements do not support that interpretation. This apparent saturation could simply reflect a non-linear dependence of the thermal resistance (between the heater and oven) on temperature. If liquid cesium plays a significant role in heat transport between the stainless steel surface and the reservoir, then vaporization of the cesium at higher temperatures would result in a higher thermal resistance. The "saturation" would then be an artifact reflecting an increasing descrepancy between the actual source temperature and the temperature measured adjacent to the heater. Clearly, it will be important to use different heater and sensor arrangements in future tests.

Using the model for the recirculating oven, we have integrated over all angles in the forward hemisphere to obtain an estimate of the total emitted flux. Similar calculations were also performed for the dark-wall and bright-wall ovens. For the conditions of the experiment described in this paper (see figure 3), the total fluxes for the bright-wall, recirculating and dark wall ovens are 3.6×10^{13}, 2.2×10^{13} and 6.2×10^{11} atoms/second, respectively. The total emission from the dark-wall oven is dramatically lower than that of either of the other ovens. This should be the ideal goal of any new oven design. For these conditions the recirculating oven is about 1.6 times as efficient in its' use of cesium as the bright-wall oven. Unfortunately, the total flux from the recirculating oven rises as T_1 rises and at T_1 = 312 K the total flux for the two ovens is about equal. For small angles (< 5°), the shape of the collimated beam changes little for this increase in T_1. It is primarily an increase in the large angle flux which produces the increased net flux for the oven. Thus, to take full advantage of the design, it is necessary to hold T_1 near the melting point of cesium (301.5 K). As will be discussed shortly, design modifications might alter this situation.

It is not surprising that the net emitted flux of the recirculating oven crosses over that of the bright-wall oven as the front temperature is increased. One only has to consider the limiting case where T_1 reaches T_2 and this becomes obvious. In this limit the source becomes essentially uncollimated with the tube area emitting flux with a cos(θ) distribution. For comparison with the figures above, the total flux (for $T_1 = T_2$ = 360.2 K) is 1.25×10^{15}, clearly much worse than for the equivalent bright-wall oven. This limiting case is also useful as a test for the integrations and the form of the equations.

The models for the three types of ovens appear to fit experimental beam profiles quite well, but their accuracy in predicting total emission has not been rigorously tested. With respect to total emission, the dark-wall and recirculating oven models would appear to rest on fairly solid assumptions, since no corrections for large angle emission seem necessary. However, as we noted in the modeling section, an end correction (not included in our calculations) is needed in the model for the bright-wall oven and this would affect the large angle emission as well as the total emission. Thus, until the models are verified, the estimates of relative total flux should be considered with care.

Several possible modifications of the simple recirculating oven can be considered. First, the oven might be designed so that the entire porous collimator is held at the front temperature T_1. For low values of T_1, the model predicts that the central beam profile for such an oven would be very close to that of the dark-wall oven (see fig. 3). However, the total integrated flux (using our experimental conditions) would not be significantly smaller than that where the wall temperature varies linearly between T_1 and T_2. This is because the large angle flux dominates the total flux and there is little difference in that flux for the two cases. Where the entire collimator is held at T_1, it might also be possible to fabricate a parallel tube structure. This type of design (which is used in ovens in commercial standards) would be problematic if the collimator had to support a large temperature gradient, since such a collimator would be short and broad, and maintenance of the temperature gradient would most likely require a very large heat flow.

Another design modification, and one that might improve the performance dramatically, involves the combination of a bright-wall and recirculating collimator. We have considered the addition of a section of bright-wall collimator at the front end of the recirculating oven described above. The model suggests that the beam profile and total flux for such a device would be very close to that of the ideal dark-wall oven. Furthermore, the performance would not be degraded as severely by a rise in T_1. In the worst case where $T_1 = T_2$, the profile and total flux would be those determined by the bright-wall part of the collimator. The key concern in the model for this hybrid oven is the validity of the assumption regarding the interface between the recirculating and bright-wall sections of the collimator. We have assumed that the vapor pressure in the bright-wall section varies linearly from zero at the emission end to a value commensurate with T_1 at the interface with the recirculating portion. The impressive potential performance of this hybrid oven clearly warrants further study.

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