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ORIGINAL ARTICLE

Decreased emission of nitrous oxide from delivery wards—case study in Sweden

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Abstract The very potent greenhouse gas nitrous oxide (N_2O) is widely used as a mild anaesthetic for mothers in delivery work in Sweden. As a part of the Stockholm County Council environmental program it was decided in 2002 that the emissions should be drastically reduced. Different ways were theoretically evaluated, and catalytic splitting to nitrogen and oxygen gas (N_2 and O_2) was chosen for a demonstration installation. A Japanese commercial unit for treatment of mixed anaesthetic gases (Anesclean® from Showa Denko K.K.) was thoroughly modified and installed at the Karolinska University Hospital at Huddinge in Stockholm in 2004. The destruction of N_2O was optimised and studied for 2 years. Data from both collection and destruction are given in the article. Of the collected N_2O more than 95% was split to N_2 and O_2 in the very stable system. The overall emission decrease was mainly dependent on the share that could be collected in the specific exhaustion system as compared to the normal room ventilation. Life cycle assessment (LCA) and life cycle costing (LCC) were used to evaluate the actual environmental value and economical cost for the process. Important factors are pointed out.

Keywords Nitrous oxide · Laughing gas · Greenhouse gas · Global warming potential · Catalytic splitting · Destruction · Decreased emission · Anaesthetic · Child delivery · LCA

1 Background

Nitrous oxide (laughing gas, N_2O) is widely used as mild anaesthetic or pain release in Swedish hospitals in connection to child delivery. It is by many anaesthetics considered to be positive since it can be administrated by the mother herself just during periods of severe pain, it is cheap, and it is without known side effects for the mothers and children (Olofsson and Irestedt 1998). However, there might be two drawbacks. Since long time exposure is not healthy (the 8 h limit value in Sweden is 100 ppm), it can be an

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occupational health problem if the gas is not properly collected and disposed of when it is breathed out. This is normally done with a separate exhaust system coupled to the administration mask.

The other problem is that N_2O is a very strong greenhouse gas, about 300 times more effective than the same amount of carbon dioxide (CO_2). Since N_2O is inert in the patient/mother, all used gas will finally end up in the atmosphere, either via special exhaustion or the regular ventilation. In 2001 Stockholm County Council (SCC) used about 40 tons of N_2O (equivalent to about 12,000 tons of CO_2), mainly in the delivery wards in their hospitals. It is normally used as a mix of 70% N_2O and 30% O_2. In 2002 SCC set up a goal to decrease the emissions by half from 2001 to 2006, and to have a first installation for N_2O destruction before the end of 2004. IVL Swedish Environmental Research Institute (IVL) got the task to suggest methods to reach these goals.

In principle N_2O can be either oxidised to NO_X ($X>0.5$), reduced to N_2 with a substance that is oxidised, or split into N_2 and O_2. Oxidation can be done with a catalyst or with normal thermal incineration. In both cases the result will be NO_X, which is also negative from an environmental point of view. Catalytic reduction of N_2O is widely investigated with different reducing agents; see i.e. Burch et al. (2002), Chaki et al. (2003) and Zhu et al. (2000). Normally insignificant amounts of CO_2 are formed from the reducing agent, but this can be completely avoided by using hydrogen gas (Arenas-Alatorre et al. 2005).

Splitting into N_2 and O_2 can be done with different catalysts and at different temperatures; se i.e. Liu et al. (2005). No real comparison between methods was made by IVL for SCC, since a reference to a commercially available unit to destroy N_2O and separate other anaesthetic gases from hospitals was found (Kai et al. 2002). Since this was the only reported similar system, and the first destruction system had to be installed soon the work concentrated on modification of this unit.

2 Description of the system

2.1 The catalytic splitting unit

The existing commercial unit, called Anesclean®, is used to treat total anaesthetic gas mixtures from surgery in Japan hospitals. Other gases than N_2O are adsorbed in columns as a first step. The second step is the splitting of N_2O in a heated catalyst bed (mainly 5% rhodium on Al_2O_3). There are two columns for adsorption, while one is adsorbing the other is desorbed and the concentrated gases are condensed by cooling. Less than 1 ppm of these gases remains after adsorption, this is important to protect the catalyst in the second step. N_2O concentration in this pre-treated air stream can be between 1 and 10%, and the volumetric capacity is 150 L/min. More than 99.5% of N_2O is split to N_2 and O_2.

A unit to treat the concentrated N_2O exhaust from all delivery rooms in Karolinska University Hospital at Huddinge would have completely other conditions. No other anaesthetics are present, the air flow varies between 1,000 and 4,000 L/min and the N_2O concentration between 0 and 10,000 ppm (0–1%). After showing in laboratory tests that the catalyst could work at high air velocities and low concentrations without giving other nitrogen containing gases, Showa Denko designed a new unit called Anesclean-SW. This was without the adsorbing step, but had a bigger catalytic bed and especially an effective heat exchange system for the high air flow. The target removal efficiency of N_2O was set to at least 85% by SCC, since higher removal efficiency was thought to require too much energy. The system that was finally installed is presented in Fig. 1.

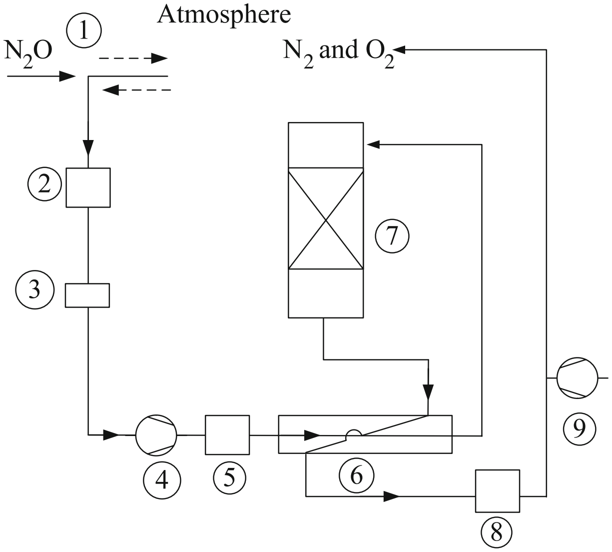


Fig. 1 Principle of the Anesclean-SW collecting system. *1* Connection to existing N_2O, *2* inlet N_2O gas meter, *3* particle filter, *4* fan that determines the capacity, *5* gas flow meter, *6* heat exchanger, *7* heated catalyst for splitting, *8* outlet N_2O gas meter, *9* fan to dilute and cool treated air

2.2 The gas collection and exhaust system

Karolinska Huddinge hospital already had a separate exhaust system from the masks providing N_2O to the mothers. The system called Anevac was installed by Medicvent AB, a Swedish medical technology company. Each double-mask both provides a mixture of N_2O and O_2, and collects the exhaust air via a separate line. The gas flow starts when a mother grabs the mask and starts to breathe in it. A central fan maintains a certain negative pressure in the system for all 11 delivery rooms. This gives a relatively efficient collection of the exhaust air from the mother. The base gas flow is about 1,000 L/min, and it increases by about 400 L/min for each mask that is used. In practice, the total air flow is very seldom over 3,000 L/min. The concentration increases with the flow rate, when there are more deliveries at the same time.

Both Anesclean-SW and Anevac have their own fans, and they have to be connected. This was done according to Fig. 2.

The flow rate into Anesclean-SW is set to a chosen value. When the flow rate from Anevac and the delivery rooms is lower than this, some air from outside the building is taken into the Anesclean-SW. When the flow rate is higher (a small portion of the time according to flow rate measurements and as shown in Fig. 6) some of the N_2O contaminated air goes outside the building, over the roof (compare 1 in Fig. 1).

3 Optimisation of the system

After the installation guarantee period with the suppliers running parameters, airflow and temperature in the catalyst were varied in a factorial experiment in the spring 2005 (Ek et al. 2005). Each set of parameters were fixed for 1 week, to decrease the influence of different amounts of births. During this period a total amount of 470 kg N_2O was treated by the Anesclean-SW system. The average concentration before treatment was 650 ppm. N_2O was only used during approximately 50% of time, the average N_2O concentration during

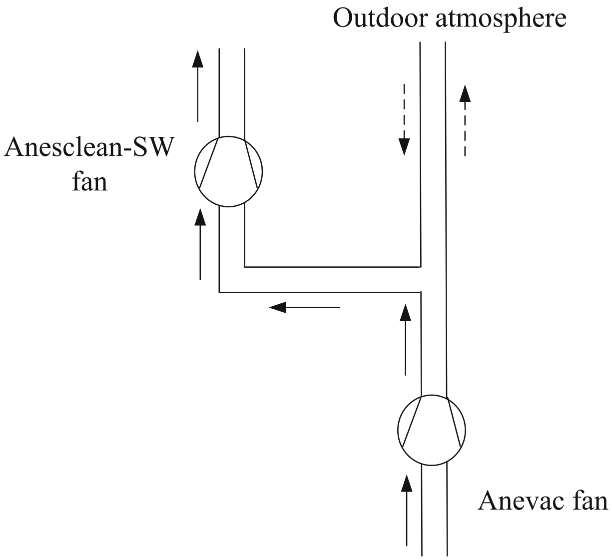


Fig. 2 The connection between Anevac and Anesclean-SW

the active time was 1,370 ppm. Figure 3 shows the reduction of N_2O concentration as a function of temperature and air flow according to the developed model.

Unfortunately, the most interesting flow rate was slightly outside the flow ranges used in the experiment, but no discontinuity was expected in the range 2.3 to 2.5 m^3/min. A higher temperature up to at least 400°C was positive under normal conditions. The splitting efficiency increased slightly with lower air flow rate, due to a longer retention time in the catalyst.

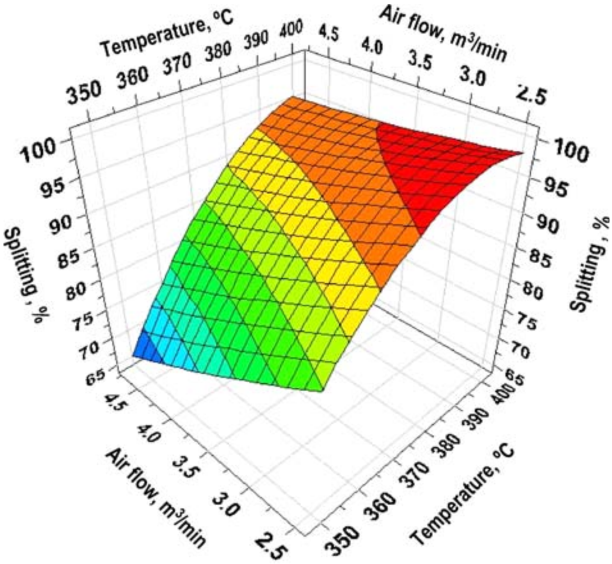


Fig. 3 Percent reduction of N_2O concentration as a function of temperature and air flow

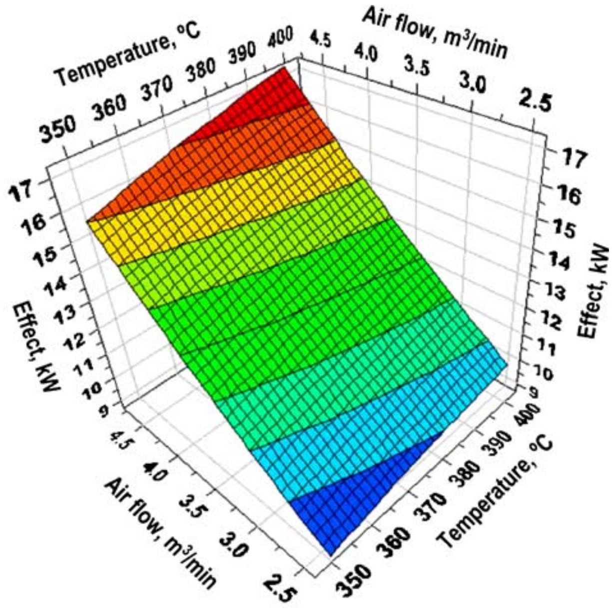


Fig. 4 Effect demand as a function of temperature and air flow

However, the amount of electric energy to run the fan and especially to heat the catalyst to the chosen temperature increased fast with increasing air flow and a little with increasing temperature, Fig. 4.

Figure 5 shows the specific energy demand per amount of destroyed N_2O. Due to the higher splitting rate at higher temperature the specific energy demand decreased with higher temperature. The specific energy demand also decreased with decreasing air flow, mainly

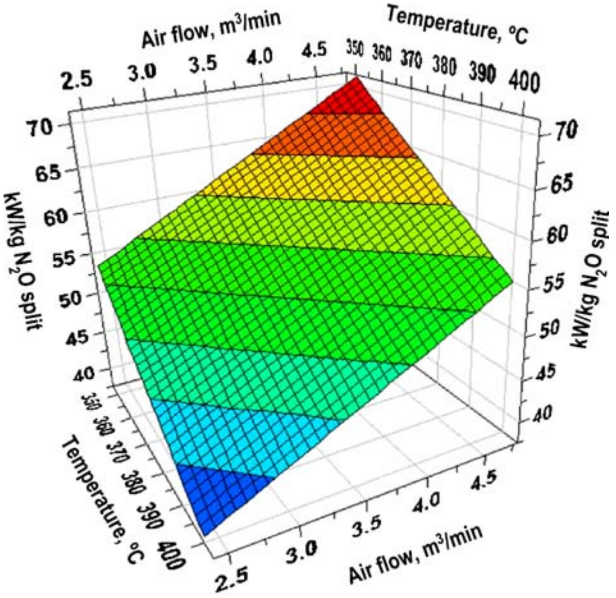
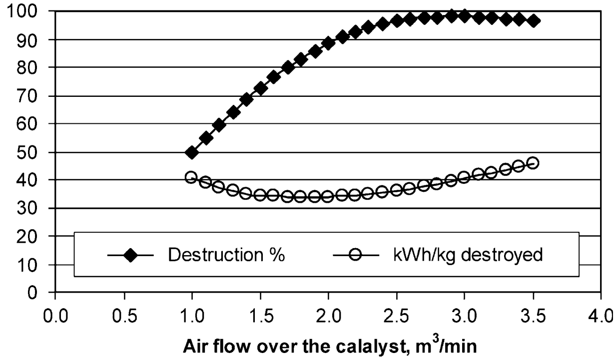


Fig. 5 Specific energy demand as a function of temperature and air flow

Fig. 6 Percent of N_2O in the exhaust air that is destroyed, and energy demand per kilogram N_2O destroyed as a function of flow rate at 400°C



due to less cooling of the catalyst. These specific relationships are of course only valid for the conditions at Karolinska Huddinge hospital.

The practical limits here are the amount of air that has to be treated from the delivery ward, and the working temperature of the catalyst. The catalyst can probably be run continuously at 450°C, but the lifetime will decrease.

For a total optimisation in this case with varying flow and concentration from the Anevac system a further optimisation of the total system has to be done. A low flow rate through the Anesclean-SW means that more of the contaminated air will be emitted without treatment. Destruction rate and specific energy demand based upon total flow rates and concentrations during the spring 2005 are shown in Fig. 6.

At too low air flow through the Anesclean-SW splitting of N_2O is complete, but a great part of the N_2O used in the delivery wards and collected by the Anevac system is lost to the atmosphere, as shown in Fig. 2. At air flow rates over 2 m^3/min enough of the N_2O is led to the Anesclean-SW to get an overall destruction over 85%. Based upon this the catalyst temperature was set to 400°C and the flow rate in the Anesclean-SW was set to 2 300 L/min (2.3 m^3/min) for longer evaluation. Measurements of the outlet flow from Anevac showed that in average 95% of the collected N_2O will be treated by the Anesclean-SW at this air flow rate.

4 Evaluation of 2 years operation

Maintenance during 2 years of operation has been 1 h per week to manually check the unit and the logged values for concentrations before and after treatment. The hospital tests its emergency power system once a month. In connection to this the power to the Anesclean-SW is broken. When it is manually started again, logged data are transferred to IVL for evaluation. Recalibration of the two N_2O meters has been needed just twice a year. Including this, change of filter and some lubrication the average time spent on maintenance is estimated to 7–8 h/month. In spite of the planned stops, the availability of the system has been well over 99%. The only non-intentional stop was that the fan stopped once in June 2006, without any obvious reason. Then the heater automatically turned off to protect the catalyst, and the alarm was shown in the central operating room.

The degradation of N_2O over the Anesclean-SW has for each week after the optimisation tests (more than 2 1/2 year) varied between 94% and 99%. There are still after 3 years of operation no obvious signs of lower capacity of the catalyst. The amount of electric energy used has varied between 30 and 45 kW h/kg N_2O split. The variation is mainly due to different amounts of N_2O used. With constant temperature and air velocity the energy demand is also constant, since the energy gained in splitting of N_2O in these concentrations has very little influence.

5 Evaluation with LCA and LCC

5.1 LCA

The environmental impacts caused by the treatment of 1 kg of N_2O with the Anesclean-SW equipment were assessed by dividing the impacts from the manufacture, transport, use and disposal by the estimated amount of N_2O fed to the Anesclean-SW during its service life (Almemark 2005). The environmental impacts from the manufacture of spare parts and accessories with a shorter service life than the apparatus itself were assessed in an analogous way.

The software KCL-ECO, version 3.1, was used for the calculations. Equipment life time was conservatively set to 10 years (except for details in fans, filters and other small parts), and the catalyst lifetime to 3 years (already shown to be realistic). Material composition of the delivered Anesclean-SW and conditions at Karolinska Huddinge hospital were used, including transport from Japan to Sweden. Recirculation of 75% of the active metal (rhodium) in the catalyst was assumed (according to Showa Denko). In this limited LCA generic data were used for manufacture of construction materials, supply of energy carriers and environmental impacts of transports construction material. The hospital uses just “Green electricity”, from hydropower. Table 1 shows the result as maximum potential environmental impacts caused by 1 kg of N_2O that is collected by the Anevac system. Figures for electricity totally from a coal power plant are also included as a worst case.

Table 1 Maximum potential environmental impact from 1 kg N_2O from Anevac, with and without Anesclean-SW (A-SW)

Impact category	Unit	Without Anesclean	With Anesclean	
			Hydro[a]	Coal[a]
Resources, non-renewable	kg	0	0.19	0.57
Resources, renewable	kg	0	0.04	0.0001
Fossil energy carriers	MJ	0	9.5	290
Non-renewable energy c. (U)	MJ	0	3	3
Renewable energy carriers	MJ	0	120	0.72
Greenhouse effect (GWP)	kg CO_2 equiv.	310	18	48
Ozone depletion potential	kg CFC-11 equiv.	0	8×10^{-8}	8×10^{-8}
Acidification potential	moles H^+	0	2.37	3.2
O_3 creation potential	kg ethylene equiv.	0	0.00032	0.003
Eutrophication potential	kg oxygen equiv.	0	0.046	0.13
Toxic compounds	kg	0	Many	Many
Heavy metals	kg	0	6.3×10^{-5}	6.3×10^{-5}
Hazardous waste	kg	0	0.0063	0.0063
Waste	kg	0	1.7	3.8

[a] Electricity for the use of Anesclean-SW is totally from either hydropower or coal

Table 2 Main causes of various potential environmental impacts by use of Anesclean-SW

Impact category	Main causes
Renewable energy carriers	Hydroelectric power for Anesclean-SW operation
Greenhouse effect (GWP)	By-passed N_2O
O_3 creation potential	Production of nickel, electronics and plastics
Acidification potential	SO_2 from production of new rhodium to catalyst
Eutrophication potential	Production of steel and transports Japan-Sweden
Toxic compounds	Mainly equipment: CO, HCl, HF, NO_X, dioxins, hydrocarbons and particles
Hazardous waste	Electronics
Waste	Mining waste

Table 2 shows the main causes of various potential environmental impacts for the studied case.

As always with evaluation of LCA different impact categories have to be compared. If you compare the five categories greenhouse effect, ozone depletion, acidification, photochemical ozone creation and eutrophication without and with Anesclean, the result is that the introduction of the Anesclean-SW very significantly reduces the greenhouse effect without causing unacceptable increases of other emissions, provided that all the impact categories are considered equally important. However, this comparison does not take into account that the use of Anesclean-SW also causes emissions of toxic compounds from the manufacture of the equipment. These emissions will hardly constitute an acute hazard at the locality where they take place. It is not possible to decide, however, whether or not the emissions of toxic compounds are acceptable in relation to the environmental benefits of a decreased greenhouse effect.

Possibilities to further improve the environmental profile of the Anesclean-SW are discussed later.

5.2 LCC

A simplified LCC was also conducted (Kock 2005). Actual costs for purchase, transport and installation and customs, the same assumptions about lifetime as in LCA, 4% interest, recovery of the catalyst and an electric energy price of 0.06 €/kW h were used. The cost/kg N_2O destroyed was calculated to almost 30 €. Over 80% of the cost was from the original delivery. This makes the cost most sensitive for changes in lifetime and interest rate, while changes in energy price would not change the cost so much. The 30 €/kg N_2O removed can for greenhouse effect be roughly compared to 0.1 €/kg CO_2 removed. Possibilities to lower specific costs are discussed in next section.

6 Possible improvements

6.1 Improved environmental profile

The positive environmental effect of Anesclean-SW at Karolinska Huddinge hospital would increase if the production of the equipment had lower environmental impact, and if the specific energy needed was lower. This unit was a prototype, and it could probably be made with less total material and also less stainless steel. It could also be produced closer to the place of use. However, most important would be to treat more N_2O per unit of time, and then also during the lifetime of the equipment. The splitting reaction is limited by the retention time in the catalyst, that is by the air flow rate. If the concentration of N_2O in the air were higher, the positive environmental effect would increase proportionally.

An increased concentration would in the same way decrease the specific energy used. The decrease would be even more than proportional, since the splitting heat could also be used. With the existing gas collection system the concentration can possibly increase by lowering the base air flow or the negative pressure in the Anevac. However this would probably lead to more losses to the regular room ventilation that is not treated. This would also risk impairing the working environment for the personnel.

Showa Denko was not willing to let the N_2O concentration in the air regulate the temperature in the catalyst, since the changes in concentration are much faster than the heating capacity. However, with the system to connect the Anevac air stream with Anesclean-SW, Fig. 2, there is another possibility. Since there are long periods when no N_2O at all is used (approximately 50% of the time no mother is using N_2O in any of the delivery rooms, it is just used during intense labour pains) there is a lot of air that can just as well be emitted directly to the atmosphere. The inlet N_2O meter could give a signal to the inlet fan (4 in Fig. 1), so concentrations below 10 ppm reduced the air flow to 10–20% of the normal. The level should be determined so the catalyst is not overheated when the flow rate decreases, and the temperature drop is not too big when the air flow increases to normal. This could decrease the energy need by up to 40%, or down to about 20–25 kW h/kg N_2O destroyed. A system like this will be tested.

6.2 Improved economy

Even with energy prices twice as high as in 2005 the above mentioned energy savings would not mean more than 5% lower total or specific cost in this specific case. Since more than 80% of the cost now is from capital costs and taxes, this is where changes would have an impact. Almost 20% of the total investment cost was taxes. This is about 15% of the total cost. Production of Anesclean-SW in longer series and a little less exclusive housing could also contribute to decrease the specific cost in a case like Karolinska Huddinge hospital to about 18 €/kg N_2O removed, or 0.06 €/kg CO_2 equivalent. This is still much higher than the current price for CO_2 emission permits, but it is lower than some actions to decrease CO_2-emissions. Most important to get a lower specific cost is a higher concentration of N_2O in the treated air.

6.3 Improved collection of N_2O

In the specific case at Karolinska Huddinge hospital the positive environmental effect would increase and the specific cost decrease if the masks could collect more of the N_2O in a more concentrated stream. However, there is an opposition against the complementing chin mask among midwives and mothers. Without this chin mask all N_2O that is exhaled after the mother has removed the double mask is lost to the regular ventilation system. As it is now, without the chin mask, about 70% of the used N_2O is collected by the Anevac system. Different ways to solve this are tested.

The average concentration of N_2O in the regular ventilation system is about 50 ppm, and treatment in a system like Anesclean-SW would be very expensive. It is possible to concentrate the N_2O in this air stream by sorption, and then desorb it in higher concentration for destruction. Such systems are investigated, and necessary to reach the new set goal by SCC to decrease N_2O emissions by 75% (with unchanged use of N_2O).

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