1. THE DGC (DOWNFLOW GAS CONTACTOR) REACTOR

The DGC (Reactor) with its ability for complete GAS ABSORPTION is a very effective gas-liquid contacting device which is simple and compact, with flexible design and easy scale up. Use of the DGC Reactor allows shorter operating and contact times, lower energy requirements, reduced capital and lower operating costs and a smaller footprint - than systems currently used, like a Scrubber.

Many applications of gas-liquid contacting for absorbing gases into liquids are found in the process industries, where a variety of different types of contacting device and methods are used. Contacting devices range from simple stirred tank reactors to complex multi-stage packed bed bubble columns and aim to provide the maximum exposure between the gas and liquid surface for maximum gas-liquid mass transfer.

Most applications employ an up-flow mode of gas flow with relatively low (< 20%) gas hold-ups along with subsequent gas disengagement with recycling, coalescence and back-mixing problems. Free gas liquid interfaces with gas pockets are formed in these reactors causing additional safety problems. Furthermore, many downflow bubble columns usually operate with jet entrainment of gas and gas bubbles therefore require subsequent disengagement and uneconomic utilization of gas whilst the interfacial area is not optimized. **USE OF THE "DGC" REACTOR ELIMINATES THE ABOVE MENTIONED DISADVANTAGES**.

The DGC reactor is an efficient MASS TRANSFER GAS-LIQUID CONTACTING/ABSORPTION DEVICE [column], where a Gas and Liquid stream are introduced simultaneously through a SPECIALLY DESIGNED ENTRY (SDI) section at the top of a fully flooded DGC column. This high velocity inlet jet stream, generates intense shear and energy, producing a vigorously agitated gas-liquid dispersion in the upper section of the column. This shear causes the break-up of any gas pocket at the inlet and allows the formation at the top of the column, of a vigorously agitated gas-liquid dispersion zone with a very high interfacial area in a small operating volume. The high degree of intense shear and turbulence caused by the incoming liquid jet, induces intense mixing and efficient mass transfer as well as constant surface renewal. A gas-liquid bubble dispersion is formed. Bubble sizes depend on the liquid characteristics (as shown in diagram and pictures below).

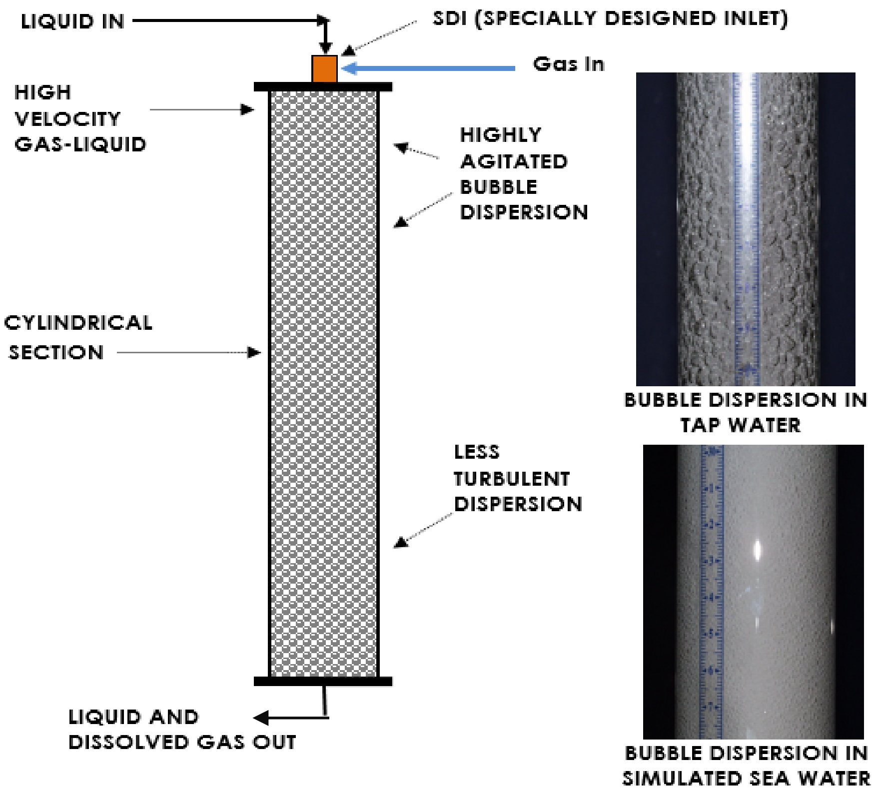


Figure 1: Schematic diagram of the DGC

The gas-liquid bubble dispersion slowly expands down the fully flooded column and the level of dispersion (and thereby volume of the gas-liquid dispersion) can be controlled by controlling the liquid and gas flow rates. In the lower section of the column, as the dispersion proceeds downwards, there is a degree of bubble coalescence since it is no longer within the region of direct inlet steam impingement. This coalescence produces larger bubbles, which rise-up the column where they are broken up by the shear of the high velocity inlet liquid jet.

Typical gas-liquid bubble dispersion achieved in the DGC is shown in Fig. 1. The pictures show the stable bubble matrix formed, which contains almost uniform sized bubbles and results in a distinct gas-liquid interface. The gas/liquid mixture can be maintained at a desired level within the Reactor to ensure 100% gas utilization (absorption). The intense turbulence, good mixing and high gas hold-up within the bubble dispersion, accounts for the efficient "gas-liquid mass transfer" performance of the DGC.

Previous studies using the DGC to evaluate Physical Absorption of gases into liquids to determine the volumetric gas-liquid mass transfer coefficient (k_La), show the potential of the DGC as an effective mass transfer contacting device.

SYSTEM	k_La s^{-1}	$k_L \times 10^4$ m/s
Air / Water	0.12 - 0.18	1.1 - 1.7
Carbon Dioxide / Water	0.21 - 0.25	1.8 - 2.6
Oxygen / Water	0.07 - 1.53	1.3 - 2.3

As per the Authors view, the most important criteria for "CARBON CAPTURE" is the EFFICIENCY of GAS ABSORPTION – which is the 'ABSORPTION' of the gas into the Absorption medium/solution used - and for this, the CRITERIA of the "GAS-LIQUID MASS TRANSFER" CAPABILITY of the Absorption system/reactor being used is of PRIMARY IMPORTANCE. The Absorption medium/solution is chosen, based on the 'reaction' of the CO2 with the specific salt used in the Absorption medium after the 'ABSORPTION' of CO2 into the liquid – which creates the concentration difference, allowing for further CO2 CAPTURE.

1.1 DESCRIPTION OF THE DGC

The specific shape, dimensions and configuration of a DGC reactor depends on the application and operating conditions required and mainly on the volumetric flowrate of the input feed gas. A DGC can be designed and operated to take into account all variations of operating conditions and applications. The DGC Reactor system also includes a Pump and Feed Vessel/Receiver connected together with necessary piping. Suitable control systems (for heating, cooling, dispersion level, pressure, liquid flowrate control, gas flowrate, data logging etc.) are included as required. A diagram of a typical DGC system is given below.

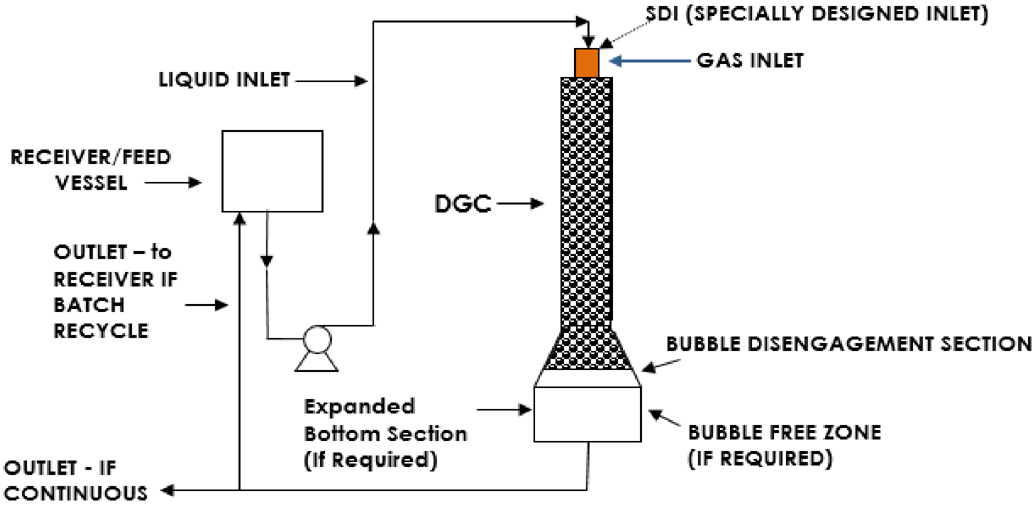


Figure 2: The DGC REACTOR System

This type of DGC with an expanded bottom section, is used when the absorption of pure gases is required, e.g. in Carbonation etc. The expanded Bubble Disengagement Section is put in, to ensure 100% utilisation (absorption) of the pure gas. By reducing the liquid velocity in the expanded section and allowing the bubble rise velocity to be higher than the downflow liquid velocity, it is ensured that there is no escape of gas bubbles and so no loss of the pure gases. The downflow liquid velocity in the column is maintained at a value below the rise velocity of the gas bubbles so that there is no tendency for the bubbles to be carried downwards. Hence there is no net movement of the gas phase whilst the liquid phase flows downwards through the inter-bubble spaces.

When operation and use of a gas mixture is undertaken for absorption of a specific gas (e.g. CO_2 in Biogas, or O2 or H2S) - there is no expanded bottom section (as shown in Figure 1 earlier) – but the DGC is a column where the liquid and unabsorbed gas (e.g. CH_4 in Biogas) passes out together from the bottom of the DGC reactor column and progresses into the Feed/Receiver Vessel where the liquid is degassed and the unabsorbed gas passes out. In this case, the liquid velocity is higher than the gas bubble rise velocity in the DGC column and so the gas bubbles pass out with the outlet liquid from the bottom of the DGC reactor.

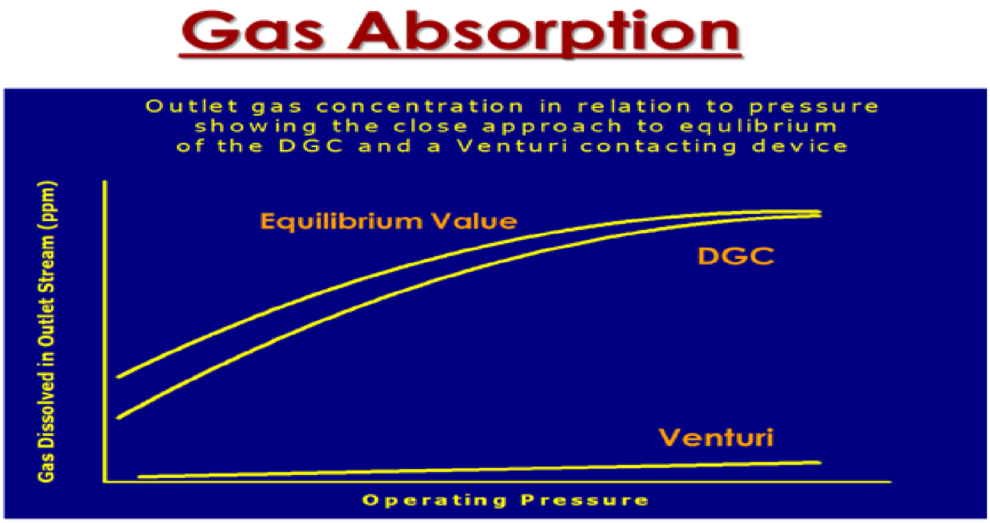
Note: The DGC can be used for both Gas-Liquid or Liquid–Liquid contacting applications – where instead of a Gas input into the main Liquid inlet stream through the SPECIALLY DESIGNED INLET (SDI), the Gas stream is replaced by a Liquid stream through the 'SDI' [e.g. Biodiesel production].

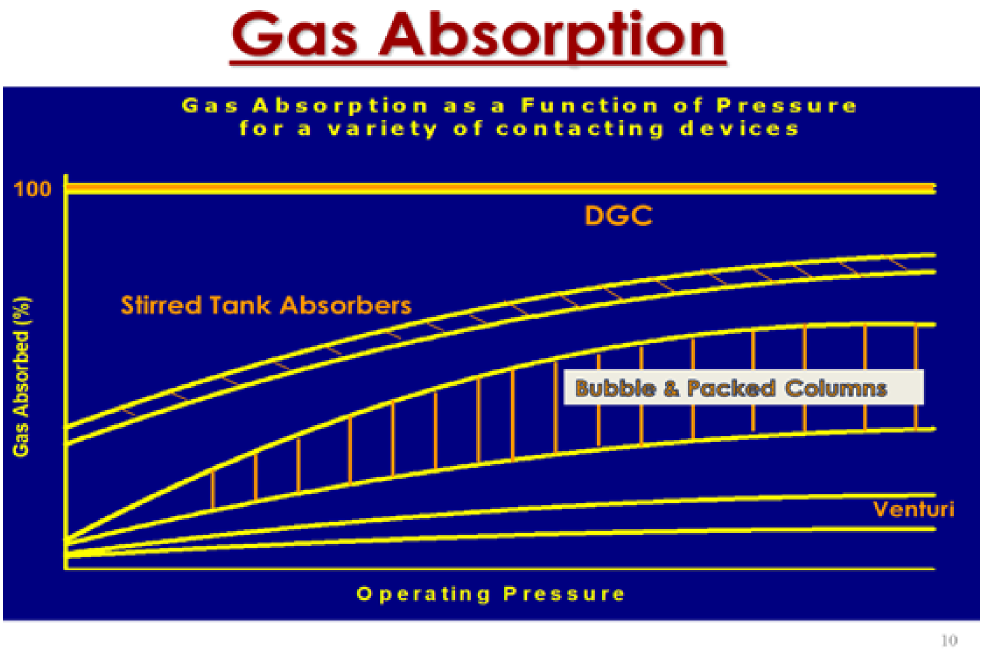
1.2 ADVANTAGES OF THE "DGC" REACTOR

The inherent simple design and operation of the DGC offers SPECIFIC ADVANTAGES over other conventional reactors and systems used for GAS ABSORPTION, such as:

- 100% GAS UTILIZATION (ABSORPTION), greater than the 95 % levels with SHORT CONTACT TIMES
- LOWER POWER CONSUMPTION. INCREASED system ENERGY EFFICIENCY
- SMALLER OPERATING VOLUME, SMALLER FOOTPRINT
- NO FOAMING possible as no free gas-liquid interface at the inlet
- Accurate and consistent CONTROL OF INTERFACIAL AREAS (1000 – 6000 m^2/m^3 depending on bubble sizes) – allows for IMPROVED GAS ABSORPTION RATES and REACTION SPECIFICITY
- No internal moving parts. REDUCED Capital (CAPEX) and Operating (OPEX) costs.
- HIGHER GAS HOLD-UPS (40-50%) - so a greater 'GAS TO LIQUID RATIO per UNIT VOLUME' is obtained
- Inlet Gas can be at either 'ATMOSPHERIC' OR 'HIGH PRESSURE' with the SDI (SPECIALLY DESIGNED INLET) being designed accordingly, based on the pressure of the Inlet Gas
- TOLERANCE TO PARTICULATES – system allows for high solid content or 'dirty' gas
- EASY SCALE-UP without loss in EFFICIENCY
- EASY AUTOMATION and CONTROL with inherently SAFE OPERATING CONDITIONS
- LOW ENGINEERING AND FABRICATION COSTS
- SIMPLE, COMPACT AND FLEXIBLE DESIGN

1.3 COMPARISONS OF THE "DGC" REACTOR 'ABSORPTION' CAPABILITIES WITH OTHER SYSTEMS





2. 'CASE STUDIES' OF GAS ABSORPTION USING A "DGC" REACTOR

Different PROJECTS - CASE STUDIES have been undertaken using the DGC Reactor involving Gas Absorption and tested for different applications:

I. KOCKUMS (Sweden): CO_2 ABSORPTION IN SEAWATER

II. TSB-INNOVATE UK: CO_2 CAPTURE FROM AIR

III. TSB-INNOVATE UK: CO_2 AND H_2S CAPTURE FROM SIMULATED BIOGAS

IV. TSB-INNOVATE UK: O_2 ABSORPTION IN AN OXYGEN/WATER SYSTEM

V. SOME FURTHER COMPARITIVE STUDIES WITH THE 'DGC' REACTOR

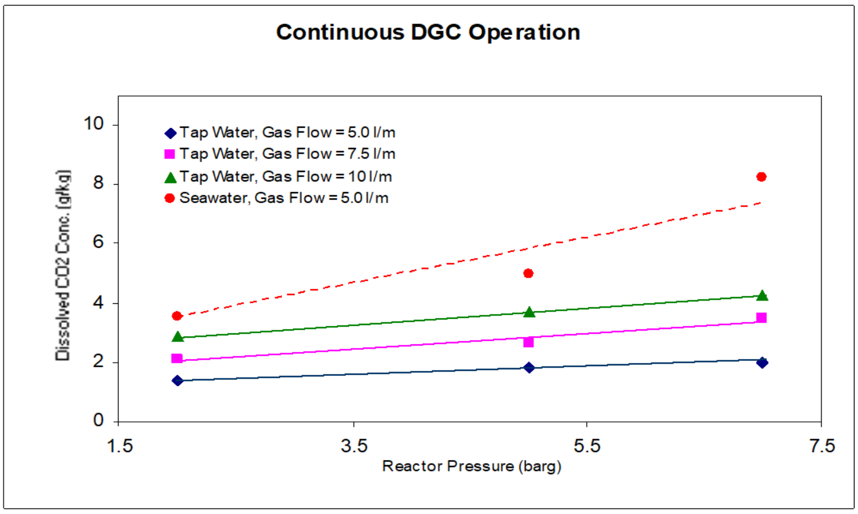
- **CASE STUDY I - <u>KOCKUMS (Sweden): CO2 ABSORPTION IN SEAWATER</u>**

A project was undertaken for an European company (KOCKUMS), who design and construct different types and models of submarines. Some of the submarines are fitted with Stirling engines which generate exhaust gas - a mixture of Carbon dioxide, Oxygen and Argon (2% O_2, 0.4% Ar, balance with CO2). WRK Design & Services Ltd. was asked to address the problem of direct discharging of such exhaust gases from submarines into seawater without degassing, in order to significantly extend the submerged endurance of conventional submarines.

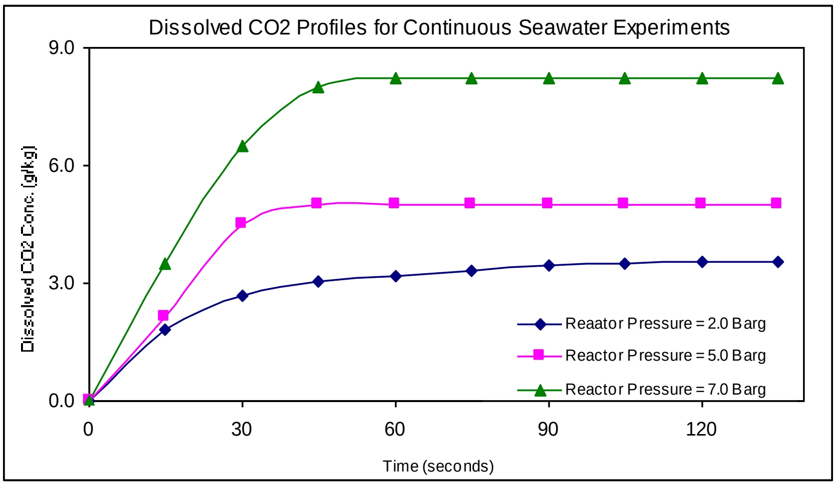
The DGC reactor was confirmed as a suitable system for contacting exhaust gases with sea water. It was concluded from the trails that a suitable DGC (Downflow Gas Contactor) Reactor can be designed and used, which would be suitable to meet the design specifications given, where 16.0 g/s of CO2 had to be absorbed in sea water, with a gas input containing a maximum of 5% Oxygen at temperatures up to 30°C, with a minimum of gas voidage less than 0.0001 in the outlet liquid, at a discharge pressure of 1.0 barg.

The CO2 concentrations achieved in tap water and seawater, under various operating conditions, varied as shown below. For the specific conditions of operation required for the submarine application, the final equilibrium concentrations achieved varied between 1.37 - 2.21 g/kg and in majority (approx 90%) of experiments the values were greater than the required value of 1.50 g/kg.

GRAPH I.1: <u>Dissolved CO_2 concentrations in water at different Pressures and Liquid Flow rates</u>



GRAPH I.2: <u>Dissolved CO2 profiles in Seawater at increasing Column Pressures</u>



- **CASE STUDY II - <u>TSB-INNOVATE UK: CO2 CAPTURE FROM AIR</u>**

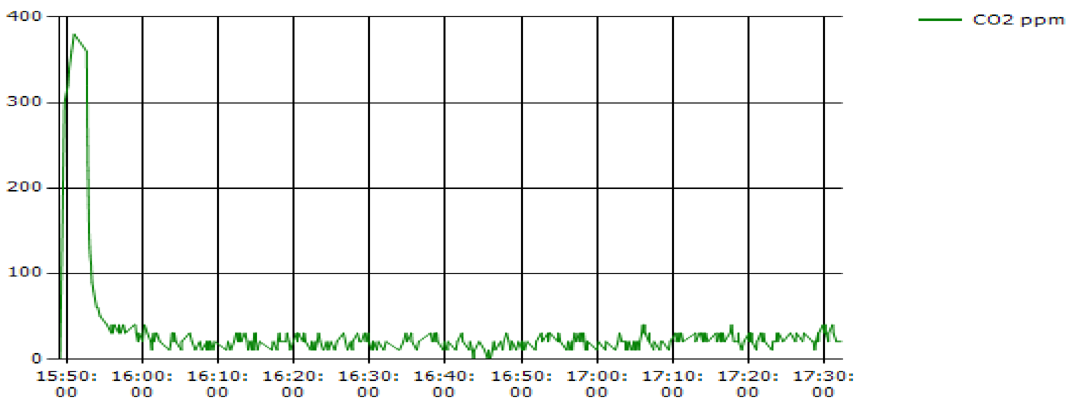
A Project, funded by the Technology Strategy Board (TSB), was undertaken with the basic objective of proving that selective capture of Carbon dioxide (CO2) from Air could be effectively undertaken in a DGC reactor.

Different formulated Absorbent solutions (based on Seawater) - ABSOLV – were used for CO2 Capture very effectively, using the DGC reactor. CO2 could be recovered by heating of the CO2 saturated ABSOLV solution.

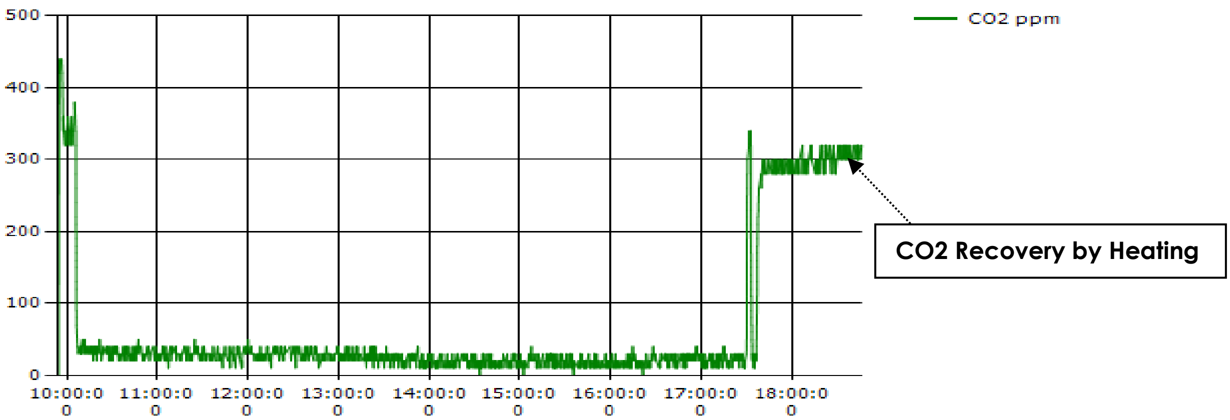
It was concluded from the trials, that the DGC unit was a very efficient system for <u>SELECTIVE CAPTURE and SEQUESTRATION of CO2 from Air</u> [reduction from 380 ppm to 10 ppm or less].

<u>SOME EXAMPLES OF 'CO2 CAPTURE' TRIALS FROM AIR</u>:

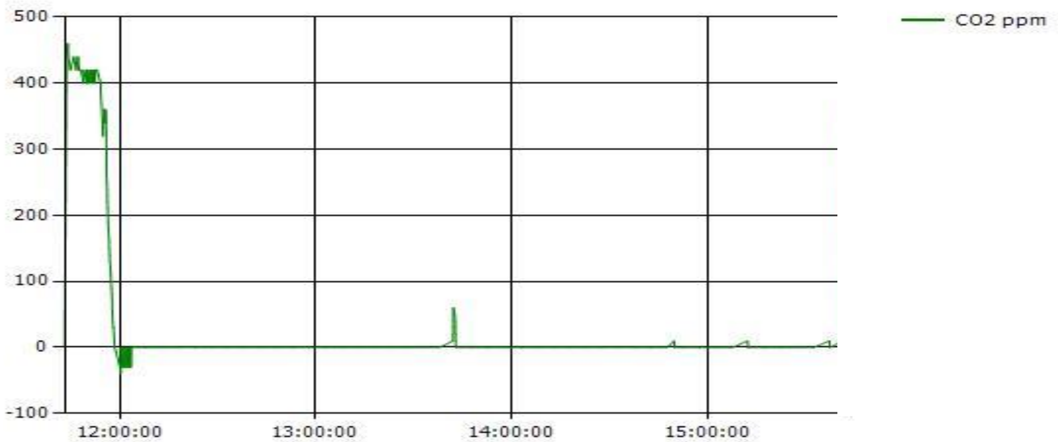
Graph II.1: – <u>ABSLOV (A) - AIR</u>



Graph II.2: <u>ABSLOV (A) - AIR</u>



Graph II.3: <u>MEA - AIR</u>



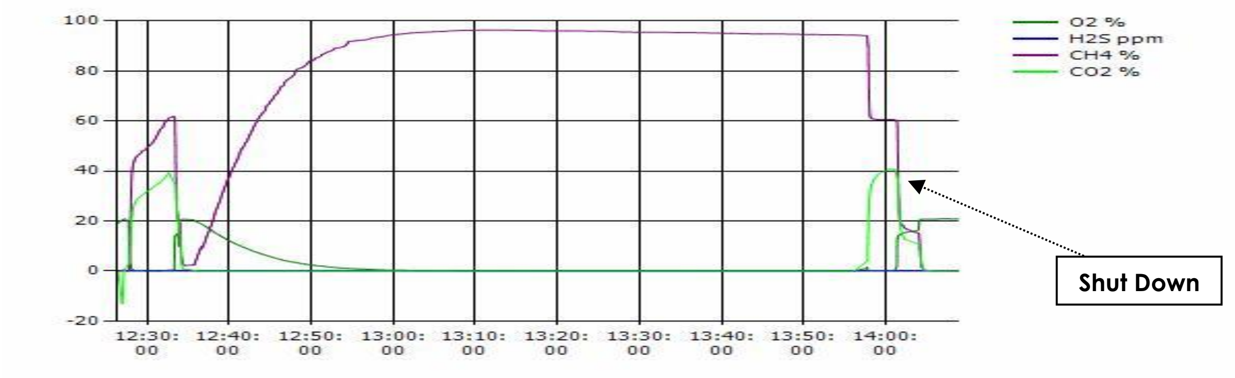
- **CASE STUDY III - <u>TSB-INNOVATE UK: CO2 CAPTURE FROM BIOGAS</u>**

A Project, funded by the Technology Strategy Board (TSB), was undertaken with the objective of Upgrading Biogas in a DGC Reactor by the selective capture of Carbon dioxide (CO2) CO2 and H2S capture from simulated biogas using WRK's formulated Absorbent solution – ABSOLV.

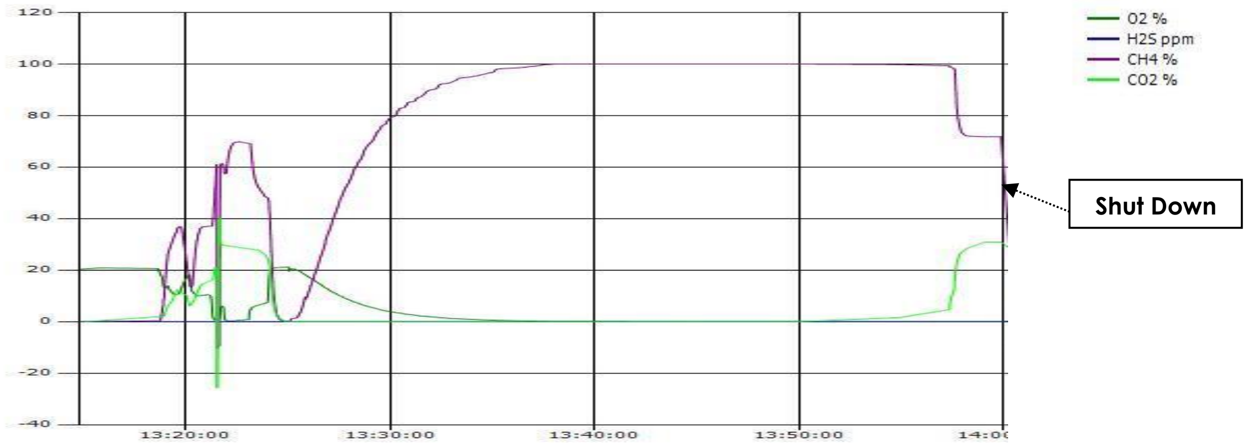
The TRIALS using simulated Biogas showed that METHANE (CH4) concentrations in the outlet attained was > 97% (even 100% in some cases) and COMPLETE ABSORPTION of the CO2 and H2S in simulated Biogas can be effected in the DGC by using an ABSORBENT SOLUTION of SPECIFIC COMPOSITION (ABSOLV), operating at the right conditions.

SOME EXAMPLES OF 'CO2 CAPTURE' TRIALS FROM BIOGAS:

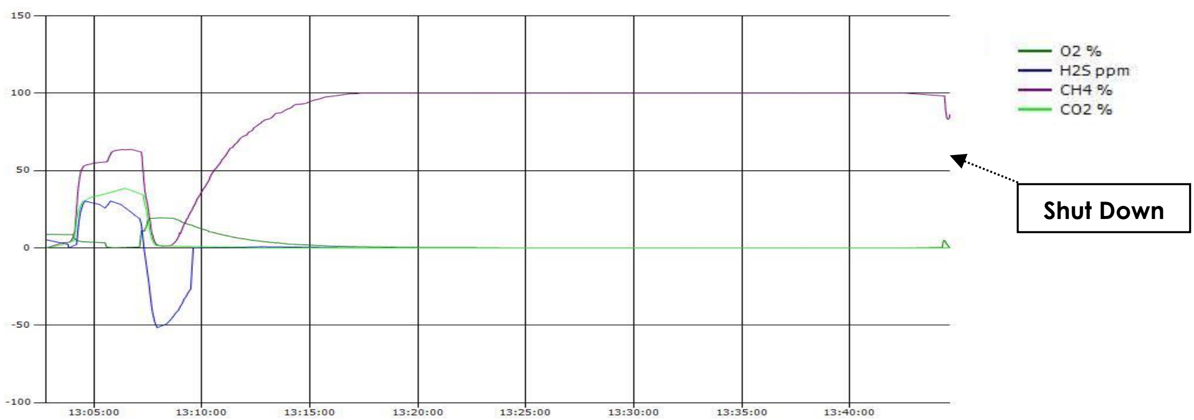
Graph III.1: <u>BIOGAS [60% CH4-40% CO2]</u>



Graph III.2: <u>BIOGAS [70% CH4-30% CO2]</u>



Graph III.3 - <u>SIMULATED BIOGAS [60% CH4-38% CO2-2% H2S]</u>



The results of the CASE STUDIES-TRIALS as given earlier, showed that that the "DGC" can be used very effectively to ABSORB/CAPTURE the CO2 content from any Gas source and also can be recovered for use as required. Salt concentrations used in the ABSORBENT LIQUID – ABSOLV (WRK) - were much lower than used in existing systems due to the very EFFICIENT GAS-LIQUID MASS TRANSFER effected in the DGC.

- **CASE STUDY IV - <u>TSB-INNOVATE UK: O2 ABSORPTION IN AN OXYGEN/WATER SYSTEM</u>**

<u>Trials of Oxygen transfer/Absorption into Water using a "DGC" Reactor</u>

Using different Inlet conditions (X) and liquid (water) flowrates for an oxygen/water system and maintaining bubble dispersions at different heights in the DGC. The volumetric mass transfer coefficient - "k_La" - was measured using a well-mixed system model and the Energy Transfer Efficiency for Oxygen Absorption (O.T.E.) was calculated for different operating conditions.

<u>RESULTS</u>:

F (liq) (l/min)	H (disp) (cm)	P (col) (psig)	k_La (s^{-1})	O.T.E (kgO2/Kwh)
Inlet condition-X				
6	42	15	0.12	6.83
6	61	15	0.13	6.20
8	21	15	0.12	3.65
8	56	15	0.17	3.49
Inlet condition-1.75X				
7	20	15	0.14	10.42
7	24	15	0.13	11.04
9.5	22	15	0.22	6.02
9.5	39	15	0.20	10.46
8	21	15	0.18	11.34
8	33.5	15	0.16	14.00
8	18.5	25	0.17	16.58
8	24	25	0.18	20.60
Inlet condition-1.15X				
6	19.5	15	0.19	3.83
6	52.5	15	0.13	4.91
5	20.5	15	0.14	8.91
5	26.5	15	0.12	9.57

- **CASE STUDY V - <u>SOME FURTHER COMPARITIVE STUDIES WITH THE 'DGC' REACTOR</u>**

DGC compared with a stirred tank for an Oxygenation process

Process Conditions	Operating Temperature	15°C
	Liquid Flowrate	10 m^3/hr
	Initial Dissolved O_2 Conc.	10 ppm
	Stirred Tank	**DGC**
Operating Pressure (Bar a)	5	4
Contact Time (seconds)	300	10
Approach to Equilibrium (%)	62.5	96
Gas Utilisation (%)	90	100
Outlet O_2 Conc. (ppm)	150	150
Volume of Adsorption Equipment (m^3)	1.5	0.05
Power Absorbed (kW)	4.8	1.2

DGC compared with a Spray Column for a Carbonylation process

Process Conditions	Operating Pressure	5 Bar a
	Liquid Flowrate	10 m^3/hr
	Initial Dissolved O_2 Conc.	10 ppm
	SPRAY COLUMN	**DGC**
Operating Temperature (°C)	5	15
Holdup Time (seconds)	80	24
Approach to Equilibrium (%)	70	97
Gas Utilisation (%)	100	100
Outlet CO_2 Conc. (ppm)	9500	9500
Saturation CO_2 Conc. (ppm)	13500	9640
Volume of Adsorption Equipment (m^3)	0.2	0.06

3. COMPARISON OF EXISTING CO2 CAPTURE/ABSORPTION UNITS & PROCESSES WITH THE 'DGC'

Among the wide range of potential applications of the 'DGC' Reactor, WRK decided to focus its effort on Carbon Capture (CO2-DGC), since it is the most market-appeal sector. The CO2 Capture technology has already been validated as shown in the results of the CASE STUDY TRIALS – given earlier. These CASE STUDY TRIALS confirmed the potentiality of "CO2-DGC SOLUTION" to reshape the GAS/LIQUID ABSORPTION technology and the more market-appealing application is the CO2 CAPTURE in Industrial facilities.

3.1 SPECIFIC COMPARISONS

Many different technologies are proposed in the CARBON CAPTURE market. A Comparison has been given, as below:

- Conventional SCRUBBERS are much bigger units than a required DGC reactor unit with higher CAPITAL (CAPEX) costs. This leads to a much cheaper and easier installation of DGC process in operating plant, which is one of the main pain points of the industrial players.
- CONTACTING EFFICIENCY of SCRUBBERS or PACKED TOWER, approximately 55-65 %, compared to 100% obtained with a DGC
- Higher concentration of Absorbent chemicals are generally used in existing process system like SCRUBBERS than were used in Trials with DGC unit. Different Absorbent solutions like MEA, have also been used successfully in the DGC but at lower Concentrations of about 0.5-1.0 M as compared to 3.0-7.0 M typically used in conventional systems like SCRUBBERS. Due to the HIGHER GAS-LIQUID MASS TRANSFER RATES, HIGHER EFFICIENCIES and GREATER GAS ABSORPTION CAPABILITIES of a DGC REACTOR, use of low concentrations are more effective, than possible in SCRUBBERS. Higher concentrations of Absorbent can be used in the DGC, if required, to get much higher Gas Absorption rates
- Higher OPERATING costs (OPEX) in present systems
- CO2 can be recovered if required and recovery system appears to be MORE COMPLEX and MORE EXPENSIVE IN EXISTING SYSTEMS, than has been seen with use of the DGC.
- There are many established processes which require HIGH PRESSURE OPERATION. The DGC can also be operated at higher pressures if required, with greater benefits. There are many established processes which require high pressure (up to 7 bar) or high temperature (up to 160°C) operation. The DGC can operate also at low pressure and ambient temperature. Moreover, the flexibility of DGC solution allows its application also in small-mid scales, while competing solutions are applied only in large scale sites.
- Adsorption through mesoporous adsorbents as activated carbon and zeolites is also undertaken in current systems, where the gas is physically adsorbed in the solid surface and the released by lowering the pressure (Pressure Swing Adsorption) - PSA. It is a matter of fact that a Conventional PSA system is much bigger than a CO2-DGC reactor, with higher capital costs due to its lower contacting efficiency (approximately 45% compared to >95% for a DGC). This leads to a much easier installation of DGC process in operating plants (one of the main pain points of the industrial players). Moreover, PSA units are characterized by a complex and expensive operational management.
- The lower volume and the lower and cheaper Absorbent salt/solution concentration required in the 'DGC' reactor process leads to a lower disruptive power consumption < 0.07 kWh/Nm3. Together the effect is that the OPEX in a DGC can be reduced by 60% (from conventional used systems) and more in respect to the traditional processes (< 10 €/ton vs. > 25 €/ton). It has been estimated that CO2-DGC is a technology which can have a realistic CARBON CAPTURE COST TARGET of 20 €/ton.

3.2 COMPARISON TABLE BETWEEN 'DGC' AND CONVENTIONAL TECHNOLOGIES

SR. NO	TECHNOLOGIES	PRESSURE SWING ADSORPTION	PRESSURIZED WATER SCRUBBING	POLYETHYLENE GLYCOL DIALKYL ETHERS - ABSORBENT	METHYL ETHYL AMINE - ABSORBENT	DI ETHYL AMINE - ABSORBENT	'DGC' DOWNFLOW GAS CONTACTOR
	CRITERIA	**PSA**	**PWS**	**GENOSORB**	**MEA**	**DEA**	**DGC**
1	**Adsorption Process**	physical	physical	physical	chemical	chemical	**physico-chemical**
2	**Pre-cleaning necessary?**	Yes	No	No	Yes	Yes	**No**
3	**Required pressure (bar)**	4-7	4-7	4-7	depressurised	depressurised	**any pressure**
4	**Required Energy consumption [kWh/Nm^3]**	0,25	<0,25	0,25-0,33	<0,15	<0,15	**0.05 – 0.07**
5	**Required temperature range [°C]**	30-50	30-40	55-80	160	160	**20 - 30**
6	**Contacting Efficiency %**	45	45	55	60	65	**100**
7	**Chemicals Concentration (M)**	0	0	3	7	5	**0.5-1**
8	**Variability of control related to load**	+/- 10-15%	50-100%	50-100%	50-100%	50-100%	**100%**
9	**Applicability**	Large Scale	Large Scale	Mid to Large Scale	Large Scale	Large Scale	**From Small to Large Scale**
10	**Carbon capture cost (€/ton)**	35-55 [#]	30-45 [*]	26-53 [#]	40-70 [**]	35-65 [*]	**20**
11	**Technology Readiness Level Assessment**	9	9	9	9	7/8	**7/8**

Table 1: COMPARISON TABLE

[http://www.ieaghg.org/docs/General_Docs/Publications/Information_Sheets_for_CCS_2.pdf
https://ec.europa.eu/clima/policies/international/negotiations/paris_en
2014 Synthesis Report Summary for Policymakers, IPCC.
http://www.globalccsinstitute.com/projects
*# *IEA greenhouse gas R&D programme Report no: PH3/26, July 2000*
*** Romeo, L.M., I. Bolea, and J.M. Escosa, Integration of power plant and amine scrubbing to reduce CO2 capture costs. Applied Thermal Engineering, 2008. 28(8): p. 1039-1046.]*

3. VALIDATION & AWARDS RECEIVED

- **CARBON TRUST (UK) – ENTREPRENEURS FAST TRACK - January 2012**

  Evaluation of DGC Technology and Business Analysis and Strategy Roadmap for the DGC Carbon Capture technology with Funding granted for Design of a 300 M3/Hr Biogas upgrading plant.

- **PATENT:**

  UK Patent No. 2504505 – "Apparatus and Method for Sequestering a Gas" – for our 'DGC' (Downflow Gas Contactor) (June 2020)

- **"SERB-IGCW 2017 Award for Green Technology"**

  Received by Indian collaborator 'STEP' at the Green Chemistry World 2017 – Conference, Mumbai, India, for the DGC Reactor technology for use in Gas Absorption, Effluent Treatment and Chemical Reactions

- **"GRAND PRIZE" & "GOLD PRIZE"**

  Received at the Seoul International Invention Fair in December 2017, Seoul, Korea, for the invention – "Carbon Dioxide (CO2) Capture using the Downflow Gas Contactor (DGC) Reactor"

- **"GOLD MEDAL"**

  Received at the 'International Conference and Exposition on Inventions by Institutions of Higher Learning 2019 (PECIPTA'19), Malaysia, September 2019 – "DOWNFLOW GAS CONTACTOR (DGC) REACTOR – ENVIRONMENTAL GREEN TECHNOLOGY DEVICE"

- **"SOLAR IMPULSE EFFICIENT SOLUTION LABEL"**

  Received for the Downflow Gas Contactor (DGC) Technology in September 2019 from the SOLAR IMPULSE FOUNDATION [World Alliance for Efficient Solutions] Geneva - supported by UNESCO, The World Bank, UN Environment etc.